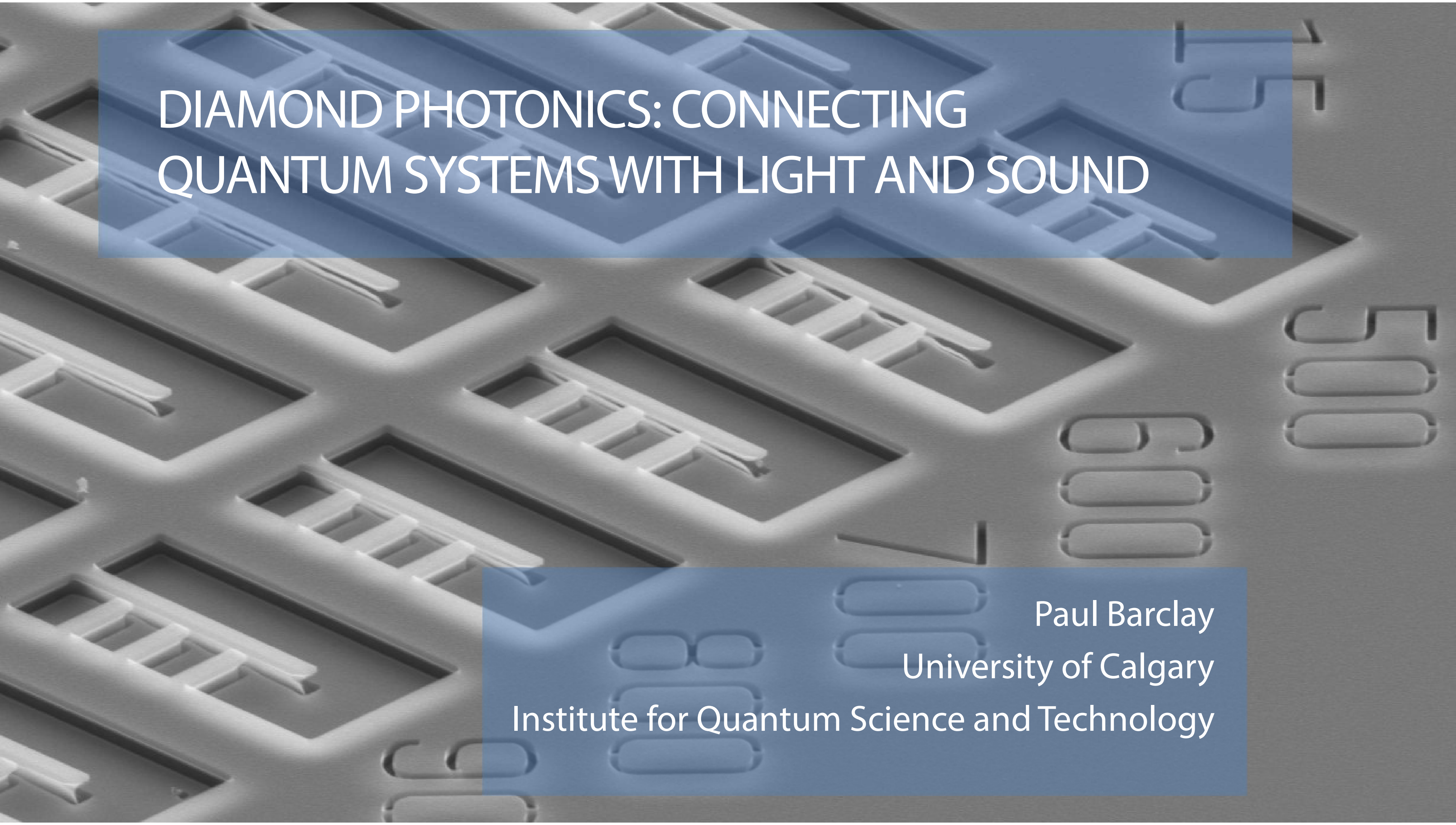


DIAMOND PHOTONICS: CONNECTING QUANTUM SYSTEMS WITH LIGHT AND SOUND

Paul Barclay
University of Calgary
Institute for Quantum Science and Technology

Outline

- Why diamond photonics?
  - Physical properties of diamond
  - Quantum photonics
- Nanofabrication
- Diamond quantum interfaces: recent advances
  - Quantum photonics
  - Optomechanics
- Challenges

Outline

Why diamond photonics?

- Physical properties of diamond
- Quantum photonics

Nanofabrication

Diamond quantum interfaces: recent advances

- Quantum photonics
- Optomechanics

Challenges

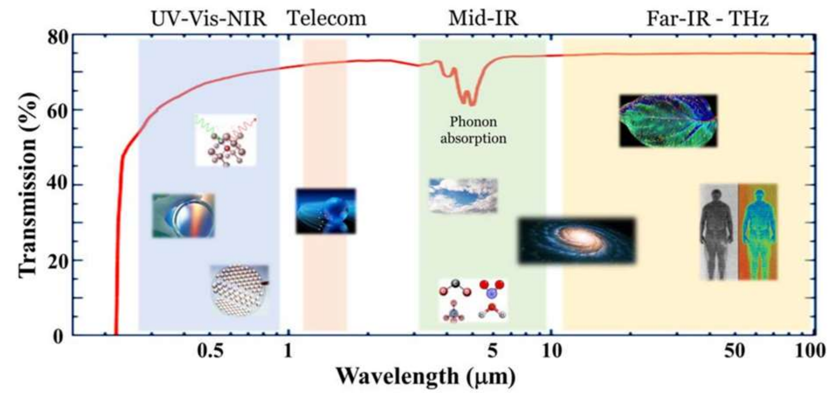
7538 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 40, NO. 23, DECEMBER 1, 2022

Diamond Integrated Quantum Nanophotonics: Spins, Photons and Phonons

Prasoon K. Shandilya, Sigurd Flågan, Natalia C. Carvalho, Elham Zohari, Vinaya K. Kavatamane, Joseph E. Losby, and Paul E. Barclay

(Invited Tutorial)

Why diamond?



Bharadwaj et al. J. Phys.: Photonics **1**, 022001 (2019)

Optics:

- Moderate refractive index (n ~ 2.4)
- Huge transparency window

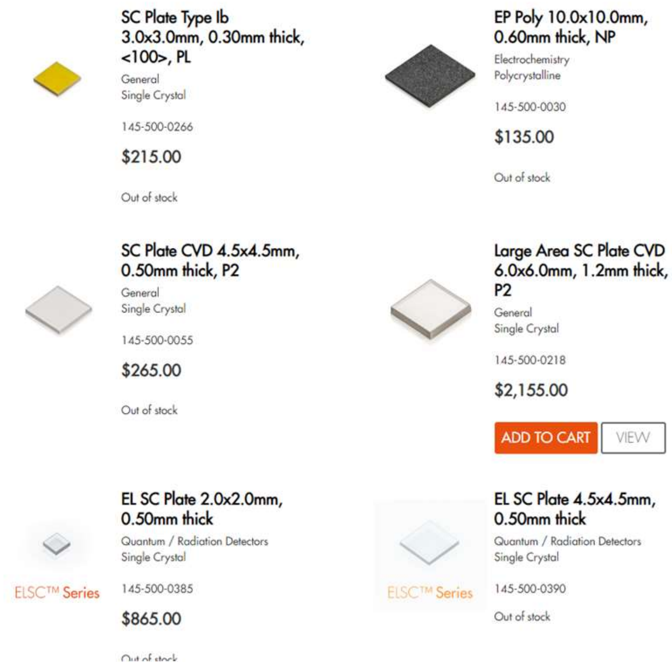
Why diamond?

CVD grown
Can be ultrapure (< 1ppb)

Available commercially
e.g. Element Six (UK)

Optics:

- Moderate refractive index (n ~ 2.4)
- Huge transparency window



https://e6cvd.com/us/application/all.html

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Available commercially
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Optics:

- Moderate refractive index (n ~ 2.4)
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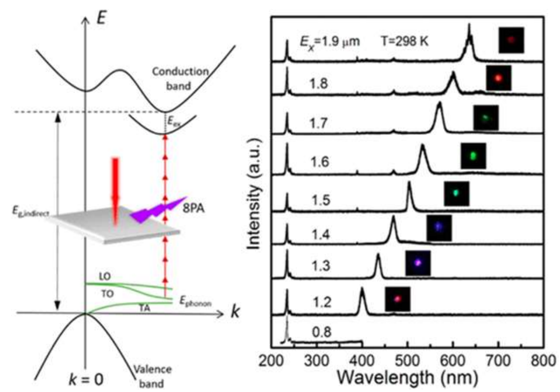
- Low multiphoton absorption



Wang et al. ACS Appl. Mater. Interfaces 10, 18935 (2018)

Why diamond?

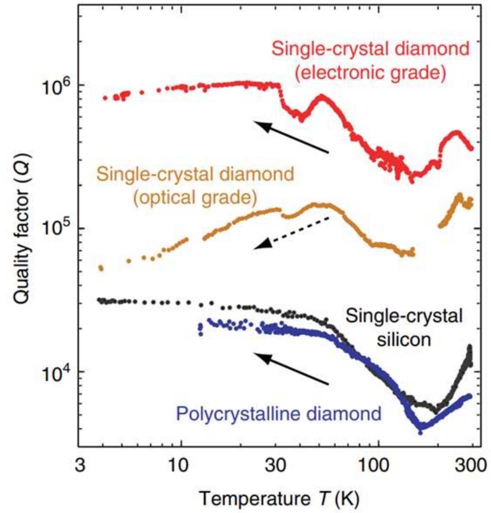
Optics:

- Moderate refractive index (n ~ 2.4)
- Huge transparency window
- Low multiphoton absorption

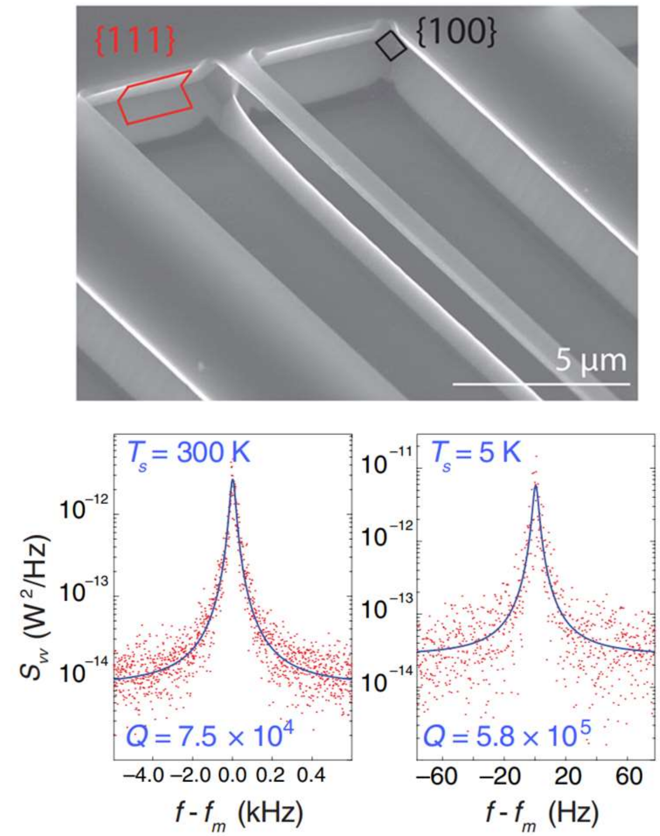
Mechanics:

Why diamond?

Tao, Degen et al. Nature Comms. **5,** 3638 (2014)



Jayakumar, Barclay et al. Phys. Rev. Appl. (2021)



Optics:

- Moderate refractive index (n ~ 2.4)
- Huge transparency window
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Mechanics:

- Ultrahigh stiffness
    - High Debye temp
- Low mechanical dissipation
- High thermal conductivity

Why diamond?

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Quantum:

Why diamond?

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Mechanics:

- Ultrahigh stiffness
    - High Debye temp
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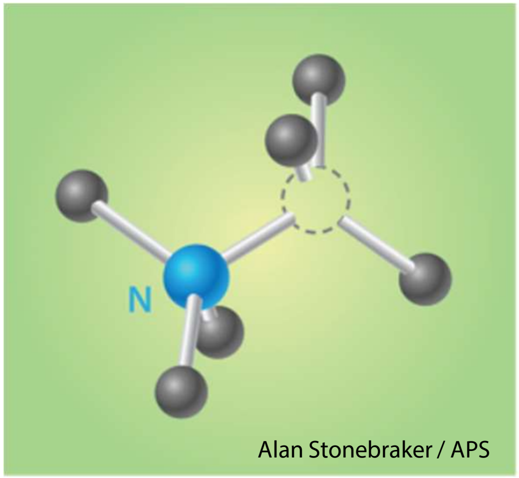
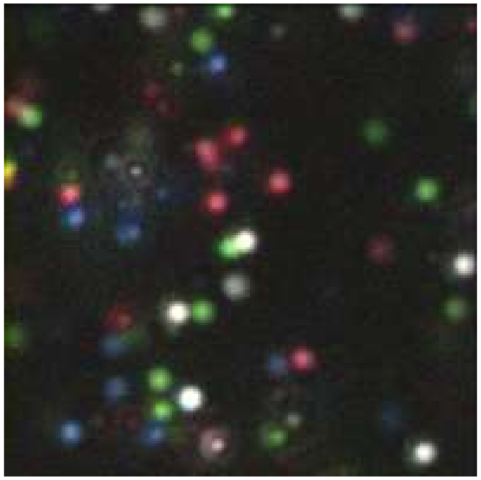
Quantum:

- Optically active defects

Why diamond?





Optics:

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- Huge transparency window
- Low multiphoton absorption

Mechanics:

- Ultrahigh stiffness
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- Low mechanical dissipation
- High thermal conductivity

Quantum:

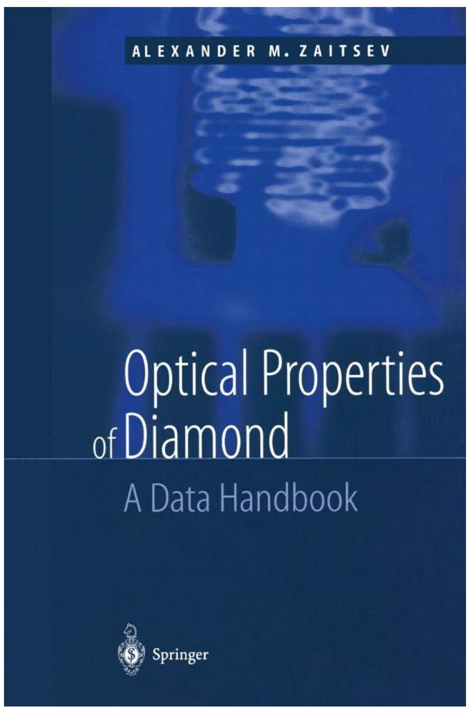
- Optically active defects/spins

Single electron spin control (~ ms @ 300K)
Single nuclear spin control (~ s @ 300K)
Indistinguishable photons (@ 4K)

Wrachtrup, Lukin, Awschalom

Quantum technologies with diamond

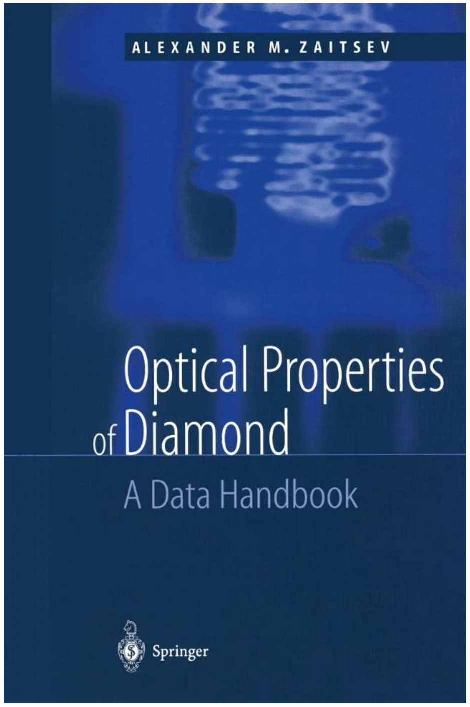
Over 100 colour centres in diamond crystals



Quantum technologies with diamond

Over 100 colour centres in diamond crystals

Studied since the 1970s



Proc. R. Soc. Lond. A. **348**, 285–298 (1976)
Printed in Great Britain

Optical studies of the 1.945 eV vibronic band in diamond

By G. Davies and M. F. Hamer
Wheatstone Physics Laboratory, King's College, Strand, London WC2R 2LS

J. Phys. C: Solid State Phys., **16** (1983) 2177–2181. Printed in Great Britain

Luminescence decay time of the 1.945 eV centre in type Ib diamond

A T Collins†, M F Thomaz‡ and Maria Isabel B Jorge‡
† Wheatstone Physics Laboratory, King's College, Strand, London WC2R 2LS, UK
‡ Departamento de Física and Centro de Física (INIC), Universidade de Aveiro, 3800 Aveiro, Portugal

J. Phys. C: Solid State Phys., **17** (1984) L233–L236. Printed in Great Britain

Persistent spectral hole burning of colour centres in diamond

R T Harley†, M J Henderson‡ and R M Macfarlane§
† GEC Research Laboratories, Hirst Research Centre, Wembley, UK
‡ Clarendon Laboratory, Parks Road, Oxford, UK
§ IBM Research Laboratory, 5600 Cottle Road, San Jose, California 95193, USA

ELSEVIER
Journal of Luminescence
Volume 38, Issues 1–6, 1 December 1987, Pages 46-47

Two-laser spectral hole burning in a colour centre in diamond

N.R.S. Reddy, N.B. Manson
Laser Physics Centre, Research School of Physical Sciences, Australia
E.R. Krausz
Research School of Chemistry, Australian National University, GPO Box 4, Canberra, ACT 2601, Australia

Abstract

Using two high-resolution lasers a short lived (~1 ms) hole burning spectrum has been observed in the 637 nm zero-phonon transition associated with the nitrogen-vacancy centre in diamond. Amongst the prominent antiholes the ones at ±2.88 GHz coincide in frequency with that obtained in EPR for a spin-doublet-singlet splitting of a metastable ^3A state. In this work it is claimed that ^3A is the ground state and this is supported by the observation of temperature-dependent magnetic circular dichroism signals. Details in the hole burning spectrum are then interpreted in terms of a strain split $^3A \rightarrow ^3E$ transition.

Quantum technologies with diamond

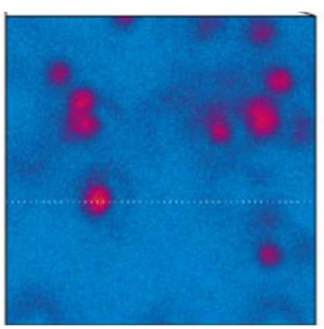
Breakthroughs: single photons

Scanning Confocal Optical Microscopy and Magnetic Resonance on Single Defect Centers

A. Gruber, A. Dräbenstedt, C. Tietz, L. Fleury, J. Wrachtrup,*
C. von Borczyskowski

The fluorescence of individual nitrogen-vacancy defect centers in diamond was observed with room-temperature scanning confocal optical microscopy. The centers were photostable, showing no detectable change in their fluorescence emission spectrum as a function of time. Magnetic resonance on single centers at room temperature was shown to be feasible. The magnetic resonance spectra revealed marked changes in zero-field splitting parameters among different centers. These changes were attributed to strain-induced differences in the symmetry of the centers.

SCIENCE • VOL. 276 • 27 JUNE 1997



RAPID COMMUNICATIONS

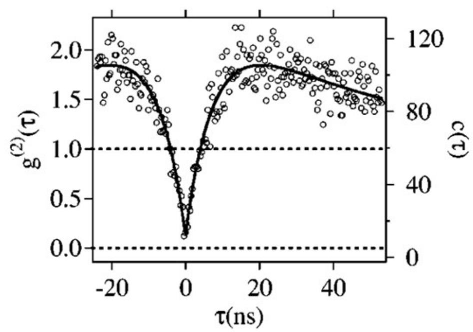
PHYSICAL REVIEW A, VOLUME 64, 061802(R)

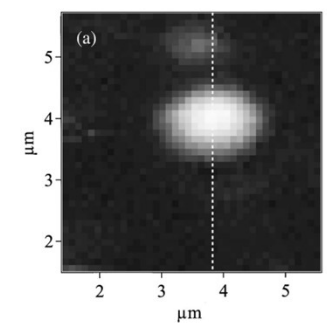
Nonclassical radiation from diamond nanocrystals

Alexios Beveratos,[1] Rosa Brouri,[1] Thierry Gacoin,[2] Jean-Philippe Poizat,[1] and Philippe Grangier[1]
[1]*Laboratoire Charles Fabry de l'Institut d'Optique, UMR 8501 du CNRS, Boite Postale 147, F-91403 Orsay Cedex, France*
[2]*Laboratoire de Physique de la Matière Condensée, Ecole Polytechnique, F-91128 Palaiseau, France*

(Received 4 April 2001; published 19 November 2001)

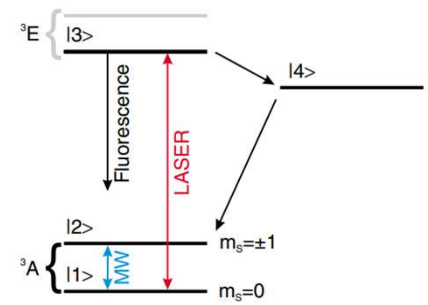
The quantum properties of the fluorescence light emitted by diamond nanocrystals containing a single nitrogen-vacancy (NV) colored center are investigated. We have observed photon antibunching with very low background light. This system is therefore a very good candidate for the production of single photon on demand. In addition, we have measured a larger NV center lifetime in nanocrystals than in the bulk, in good agreement with a simple quantum electrodynamical model.





Quantum technologies with diamond

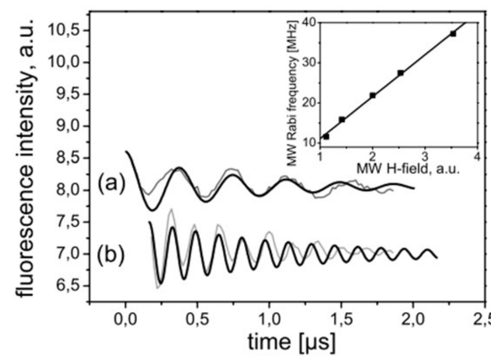
Breakthroughs: single spins at room-T



VOLUME 92, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 20 FEBRUARY 2004

Observation of Coherent Oscillations in a Single Electron Spin

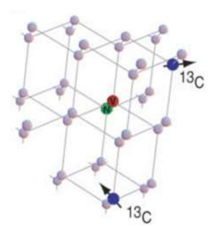
F. Jelezko, T. Gaebel, I. Popa, A. Gruber, and J. Wrachtrup
3. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany
(Received 2 September 2003; published 20 February 2004)



Coherent Dynamics of Coupled Electron and Nuclear Spin Qubits in Diamond

L. Childress,[1]* M. V. Gurudev Dutt,[1]* J. M. Taylor,[1] A. S. Zibrov,[1] F. Jelezko,[2] J. Wrachtrup,[2] P. R. Hemmer,[3] M. D. Lukin[1]†

SCIENCE VOL 314 13 OCTOBER 2006



Quantum technologies with diamond

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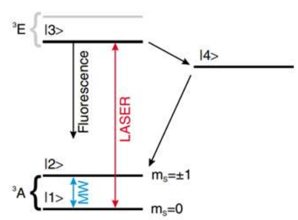

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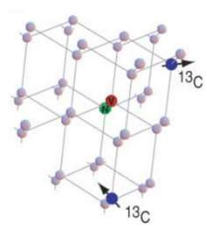
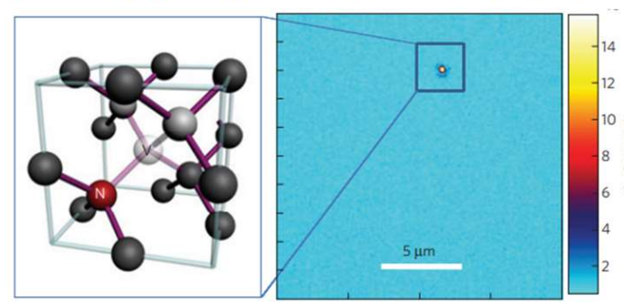


nature materials LETTERS
PUBLISHED ONLINE: 6 APRIL 2009; CORRECTED ONLINE: 14 APRIL 2009 | DOI: 10.1038/NMAT2420

Ultralong spin coherence time in isotopically engineered diamond

Gopalakrishnan Balasubramanian[1], Philipp Neumann[1], Daniel Twitchen[2], Matthew Markham[2], Roman Kolesov[1], Norikazu Mizuochi[1,3], Junichi Isoya[3], Jocelyn Achard[4], Johannes Beck[1], Julia Tissler[1], Vincent Jacques[1], Philip R. Hemmer[5], Fedor Jelezko[1]* and Jörg Wrachtrup[1]*



Aside: quantum sensing with spins

APPLIED PHYSICS LETTERS **92**, 243111 (2008)

Scanning magnetic field microscope with a diamond single-spin sensor

C. L. Degen[a)]
IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120, USA

High-sensitivity diamond magnetometer with nanoscale resolution

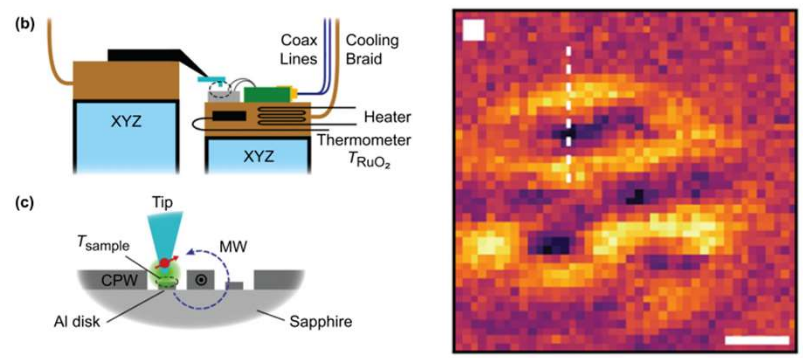
J. M. TAYLOR[1]*, P. CAPPELLARO[2,3]*, L. CHILDRESS[2,4], L. JIANG[2], D. BUDKER[5], P. R. HEMMER[6], A. YACOBY[2], R. WALSWORTH[2,3] AND M. D. LUKIN[2,3†]

nature physics | VOL 4 | OCTOBER 2008 |

Scanning nitrogen-vacancy magnetometry down to 350 mK

Cite as: Appl. Phys. Lett. **120**, 224001 (2022); doi: 10.1063/5.0093548
Submitted: 29 March 2022 · Accepted: 11 May 2022 ·
Published Online: 31 May 2022

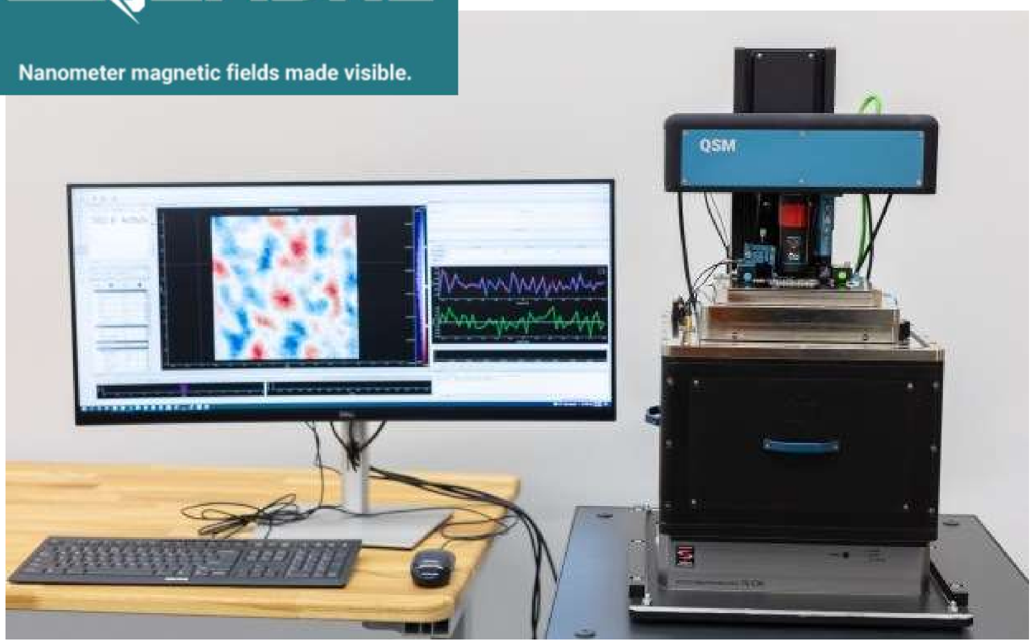
P. J. Scheidegger,[1] S. Diesch,[1] M. L. Palm,[1] and C. L. Degen[1,2,a)]

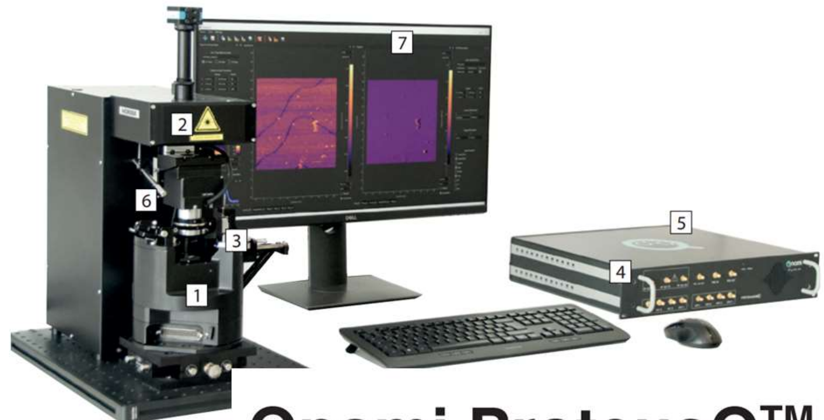


Aside: quantum sensing with spins

ZABRE

Nanometer magnetic fields made visible.





Qnami ProteusQ™

Capture surface magnetic fields at the atomic scale

Quantum technologies with diamond

Breakthroughs: quantum spin-photon entanglement

Quantum entanglement between an optical photon and a solid-state spin qubit

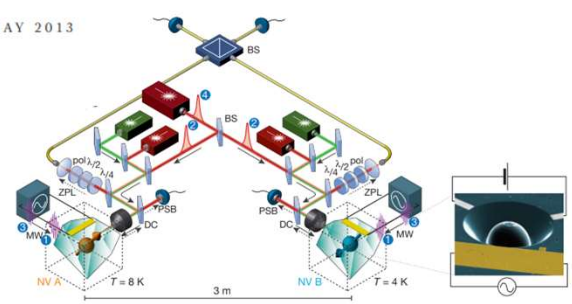
E. Togan[1]*, Y. Chu[1]*, A. S. Trifonov[1], L. Jiang[1,2,3], J. Maze[1], L. Childress[1,4], M. V. G. Dutt[1,5], A. S. Sørensen[6], P. R. Hemmer[7], A. S. Zibrov[1] & M. D. Lukin[1]

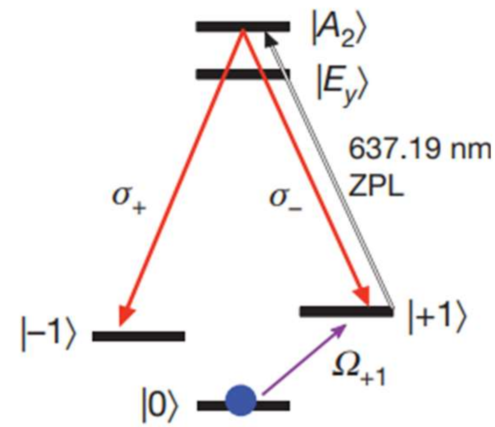
NATURE | Vol 466 | 5 August 2010

Heralded entanglement between solid-state qubits separated by three metres

H. Bernien[1], B. Hensen[1], W. Pfaff[1], G. Koolstra[1], M. S. Blok[1], L. Robledo[1], T. H. Taminiau[1], M. Markham[2], D. J. Twitchen[2], L. Childress[3] & R. Hanson[1]

86 | NATURE | VOL 497 | 2 MAY 2013

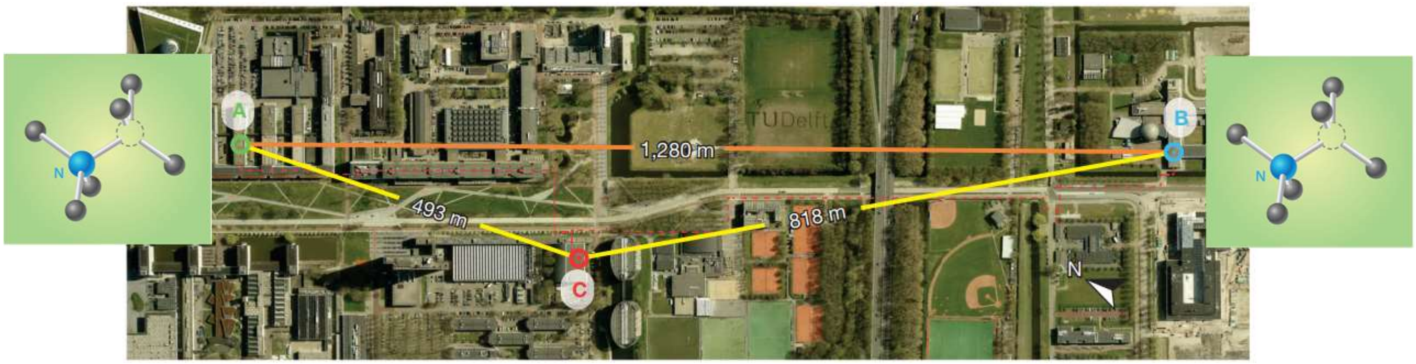




Quantum technologies with diamond

Breakthroughs: violating Bell's inequalities and quantum networking

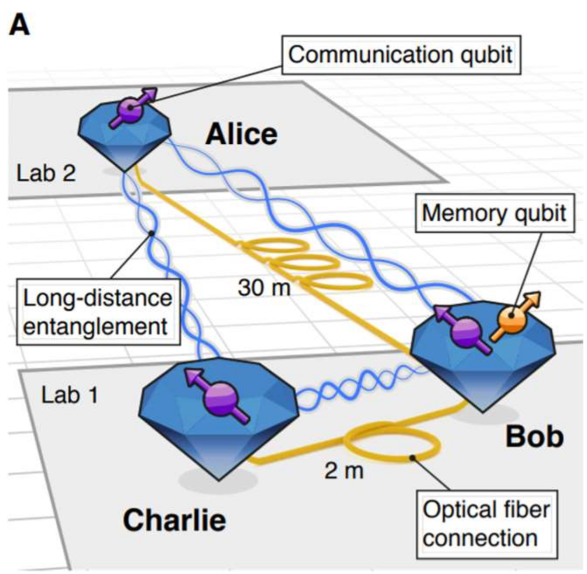
TU Delft / Hanson group



First demonstration of loophole free violation of Bell's inequalities: Nature 526, 682 (2015)

Quantum technologies with diamond

Breakthroughs: violating Bell's inequalities and quantum networking

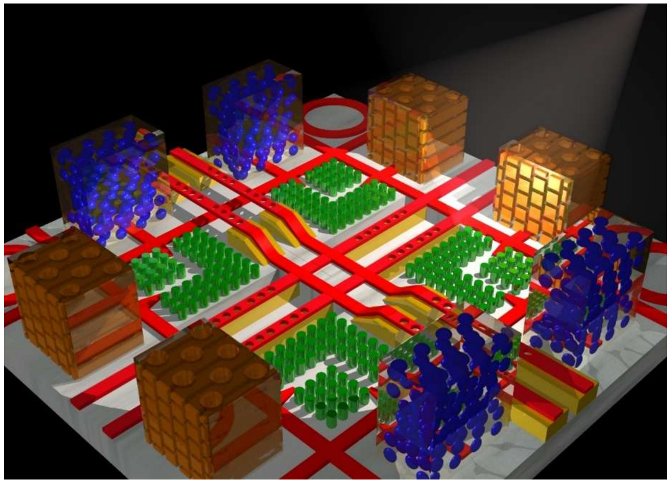


TU Delft / Hanson group

Realization of a multi-node quantum network of remote solid-state qubits
Science 372, 259 (2021)

The role of nanophotonics in quantum networks

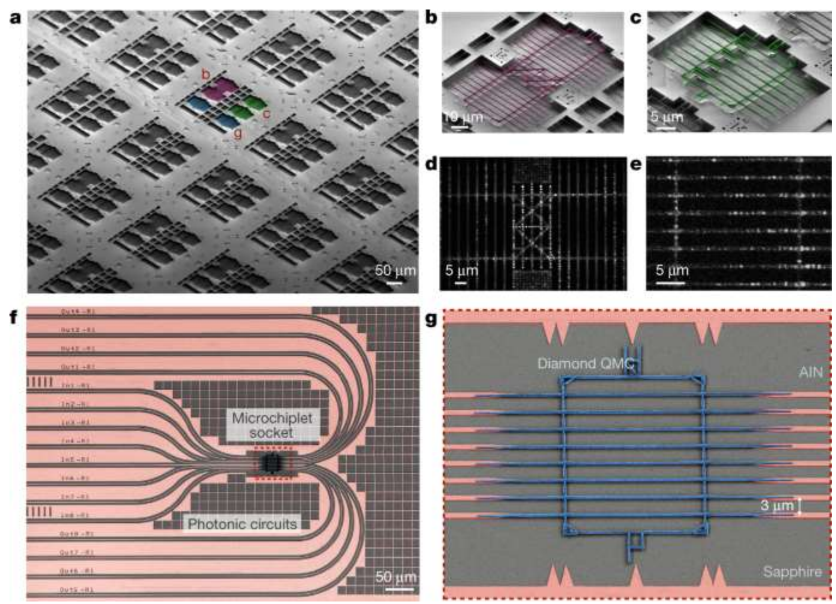
Wiring qubits together



Joannopoulos textbook circa 1995

The role of nanophotonics in quantum networks

Wiring qubits together – e.g. Lukin, Englund, Fu, Faraon, Waks etc.

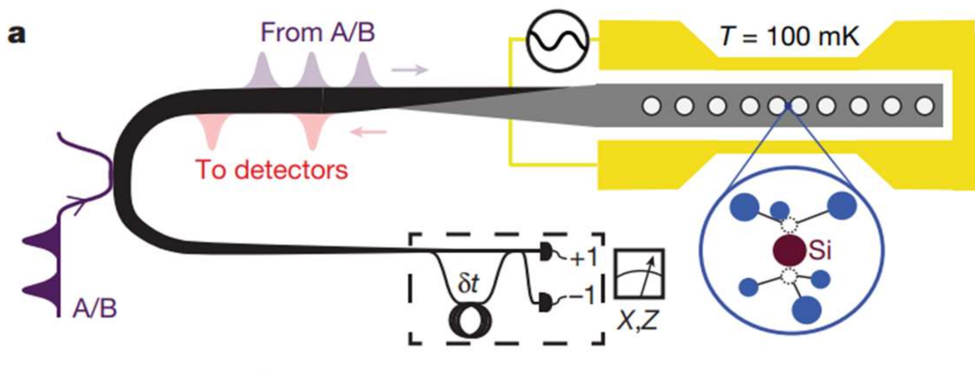


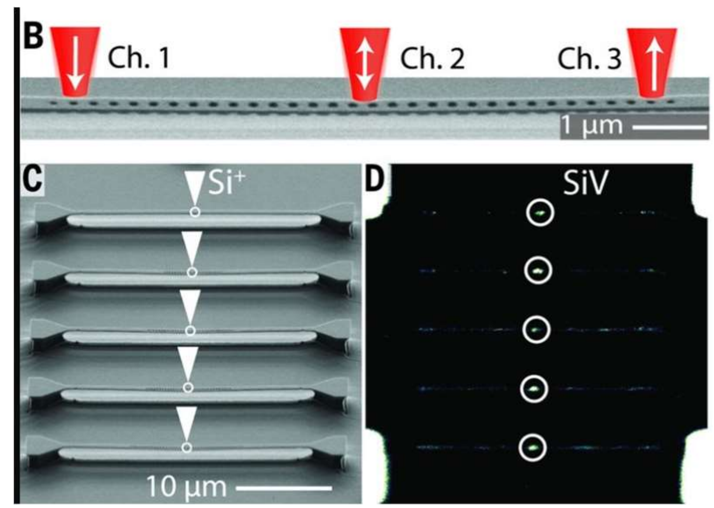
Wan, Englund et al. Nature **583**, 226 (2020)

The role of nanophotonics in diamond quantum photonics

Wiring qubits – e.g. Lukin, Englund, Fu, Faraon, Waks etc.

Increasing emission rates – Purcell effect





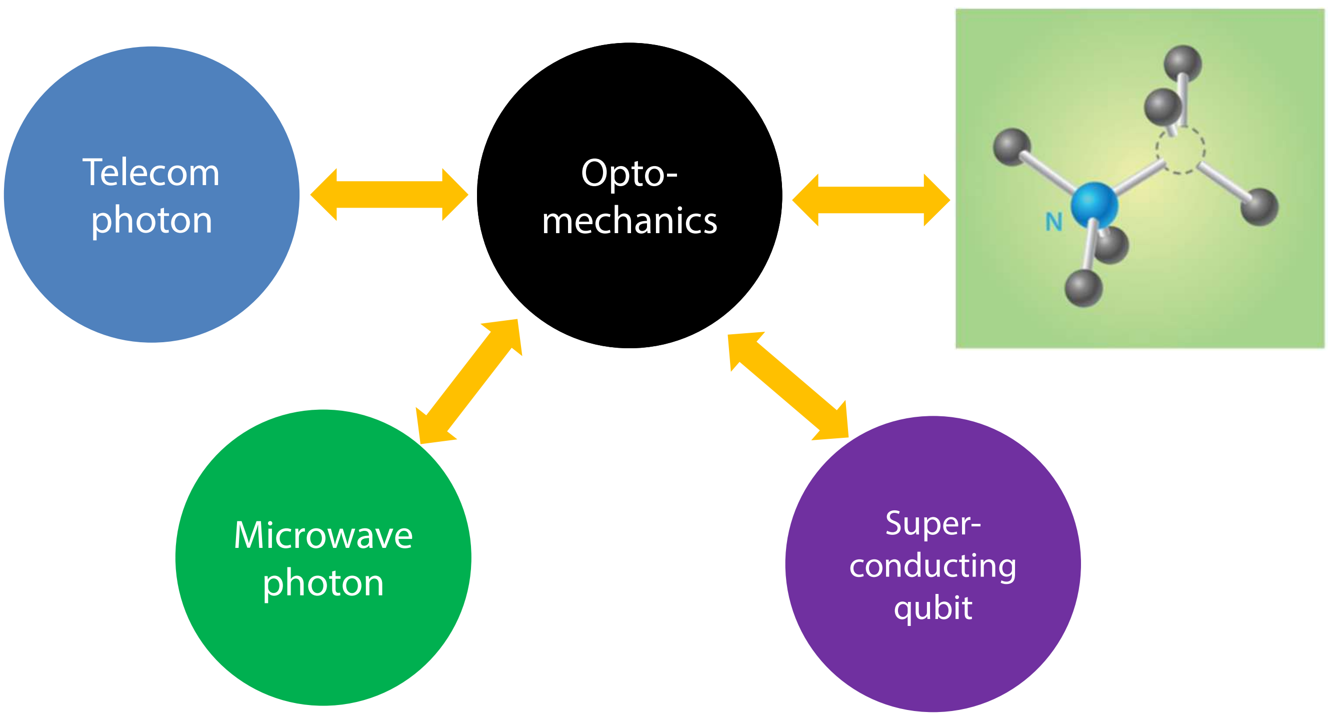
Bhaskar et al. Nature **580**, 60 (2020)

The role of nanophotonics in diamond quantum photonics

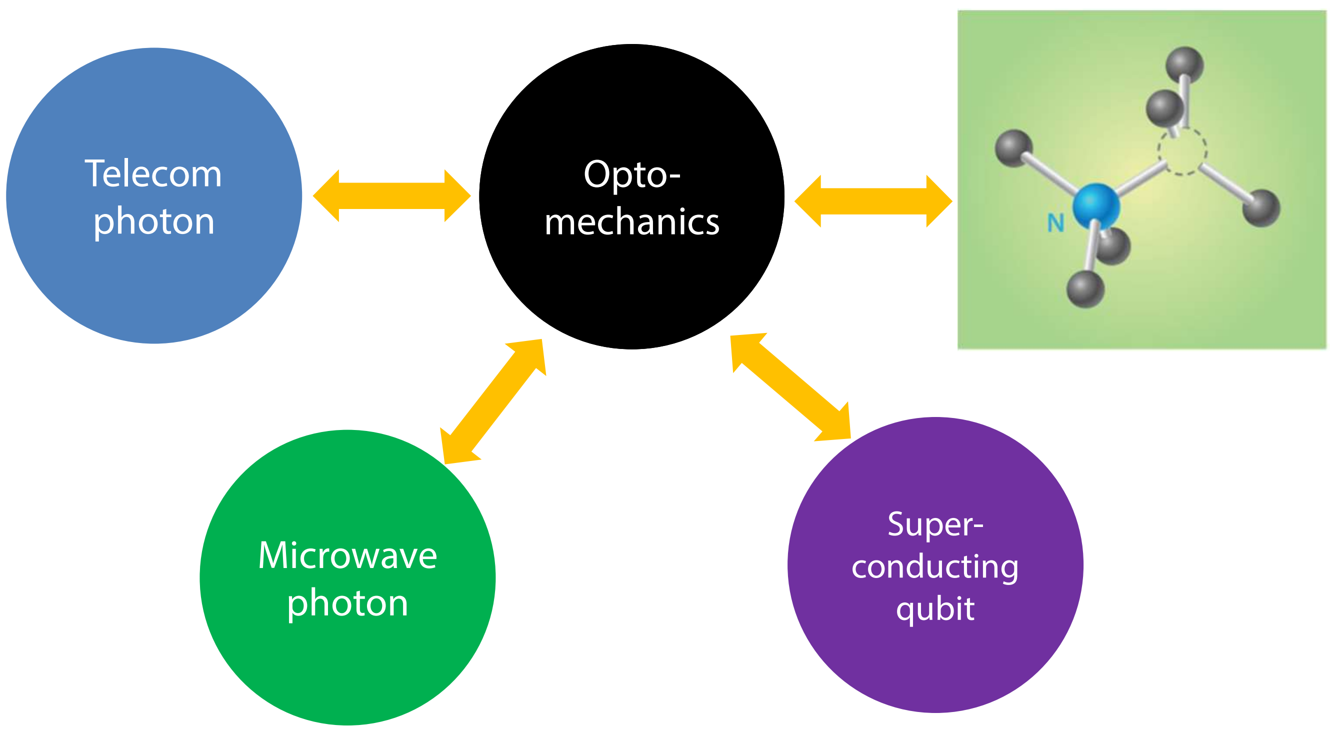
Wiring qubits – e.g. Lukin, Englund, Fu, Faraon, Waks etc.

Increasing emission rates – Purcell effect

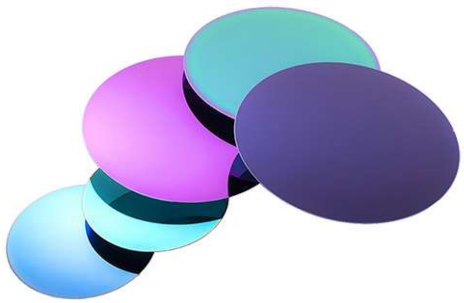
Converting information between mediums



Quantum transducers

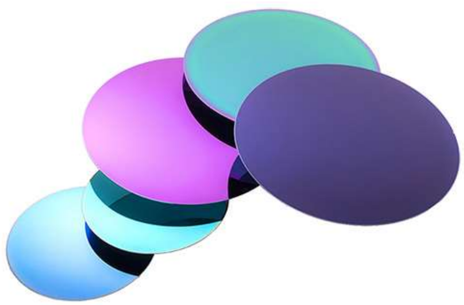


Diamond nanofabrication



Wafer scale thin films available for conventional photonic materials: Si, SiN, GaAs, etc.

Fabricating diamond devices



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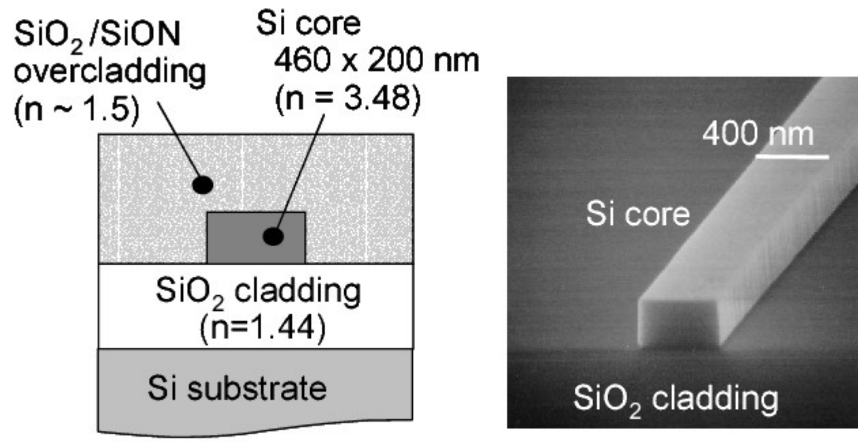
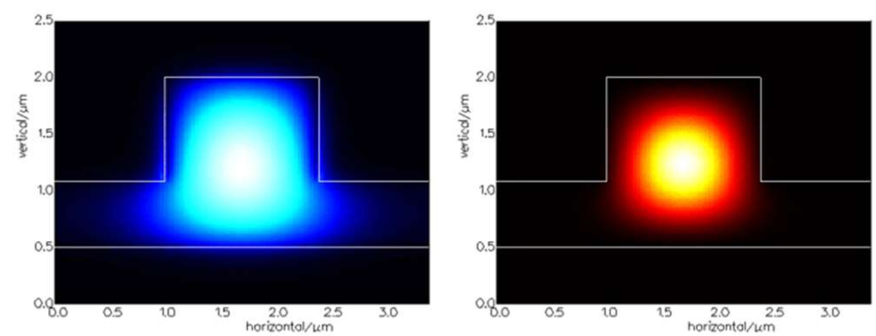
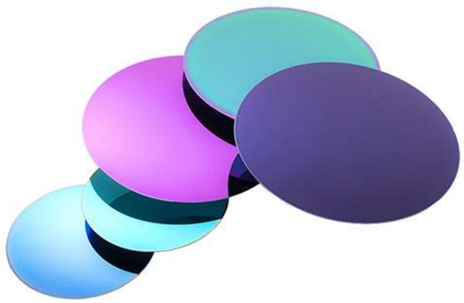


Fig. 1. Schematic of silicon photonic wire waveguide.



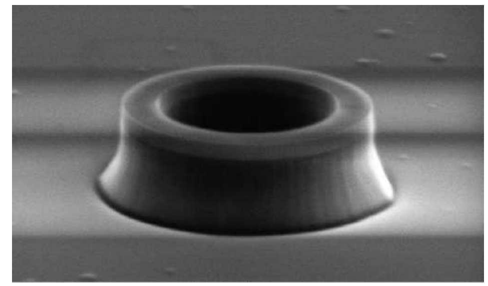
Fabricating diamond devices

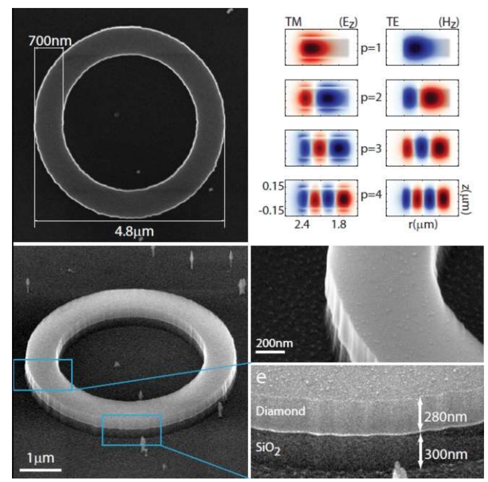


Wafer scale thin films available for conventional photonic materials: Si, SiN, GaAs, etc.

How to create suspended **single crystal** diamond devices without thin films?

Single crystal diamond devices: brief history





Quantum nanophotonics:

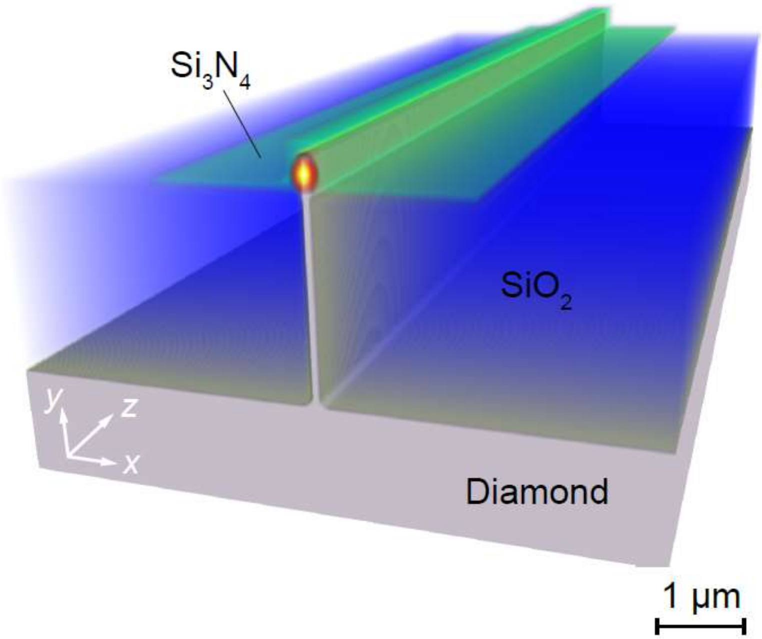
- Enhanced zpl photon generation
  - Faraon, Barclay et al., Nat. Photonics 2011
  - Riedrich-Möller, Becher et al., Nat. Nano. 2012
- Efficient photon collection
  - Babinec, Loncar et al., Nat. Photonics 2010
- Nonlinear optics
  - Hausmann, Loncar et al., Nat. Photonics 2014
- Elements of quantum networks
  - Li, Schroeder, Englund et al., Nat. Comm. 2015

Nanomechanics

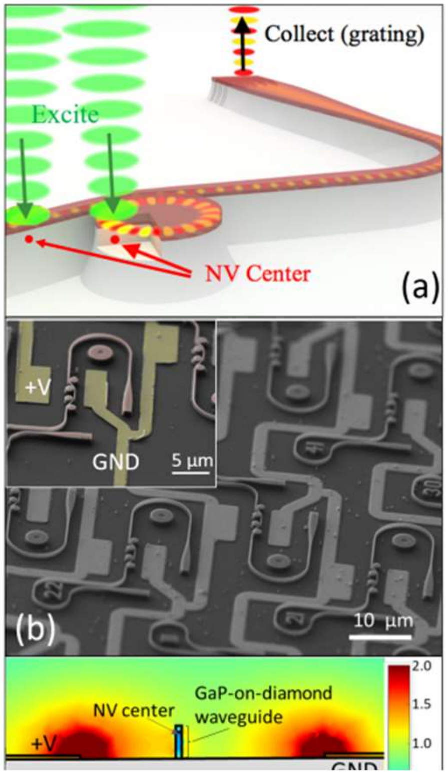
- Scanning spin magnetometers
  - Maletinsky, Loncar, Lukin et al., Nat. Nano. 2012
- Ultrahigh Q cantilevers
  - Tao, Degen, et al. Nat. Comm. 2014

Optomechanics: today's results

Fabricating diamond devices



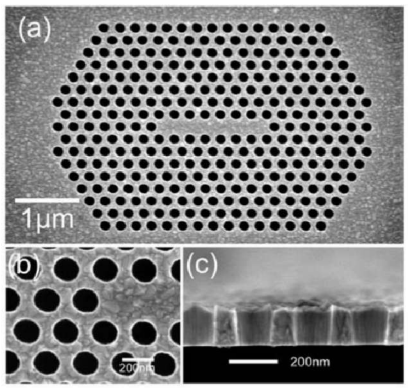
Grote, R & Bassett, L; [APL Photonics 2016 Aug 1; 1(7): 1302]

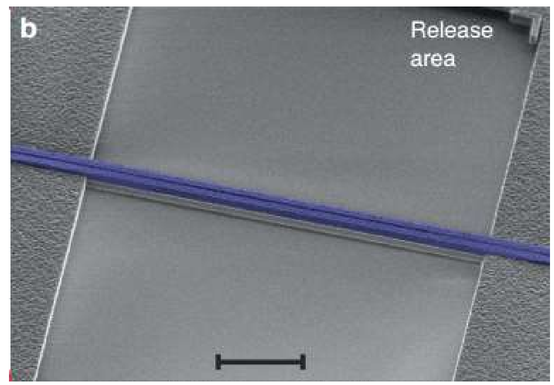


Schmidgall, Fu et al. Nano Lett. **18**, 1175 (2018)

Evolution of diamond fabrication

Polycrystalline diamond devices: Pernice, Hu, others (2007 – onward)

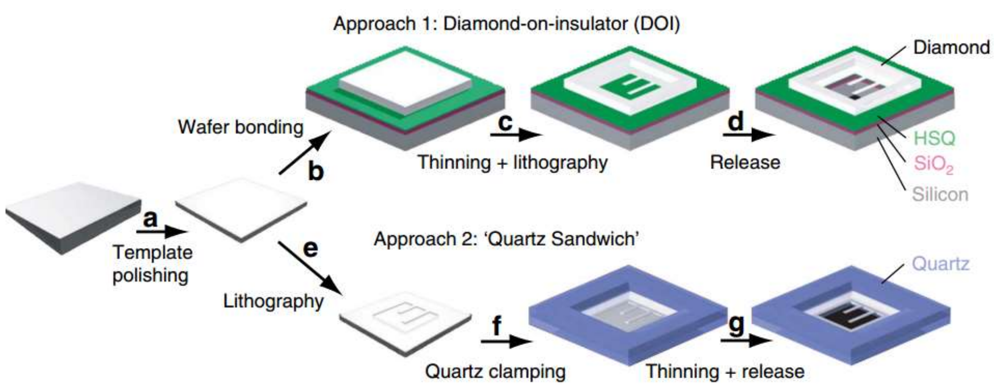




Hybrid devices: Barclay/Fu/Santori (2008 – onward)

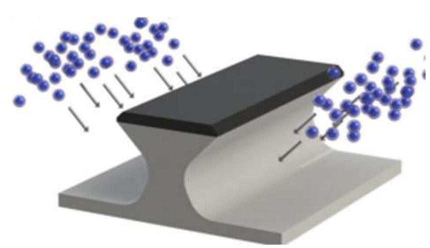
Evolution of diamond fabrication

Thin diamond films: Faraon, Loncar, Jayich, Degen (2010 –)



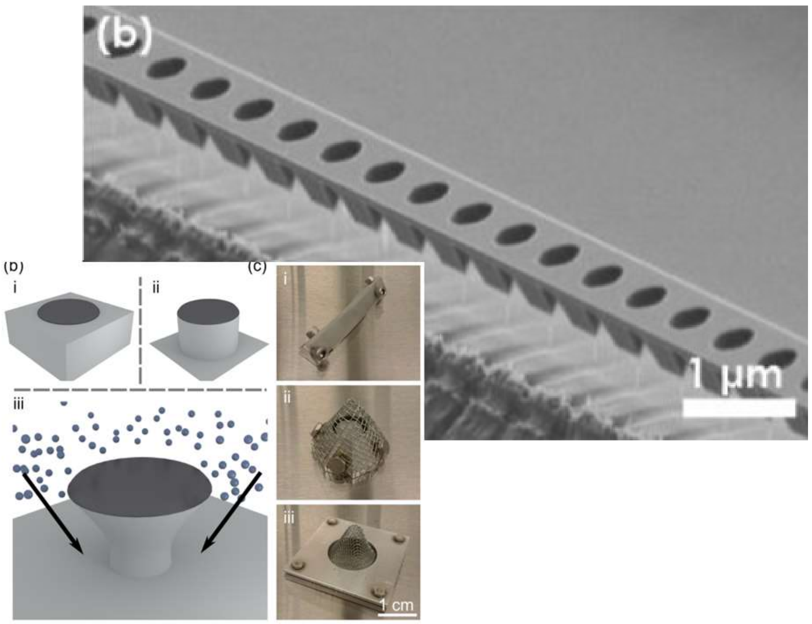
Ion milling: Prawer (2005), Loncar (2011), Becher (2012)

RIE angle etching: Loncar (2013)



Two new 3D etching techniques

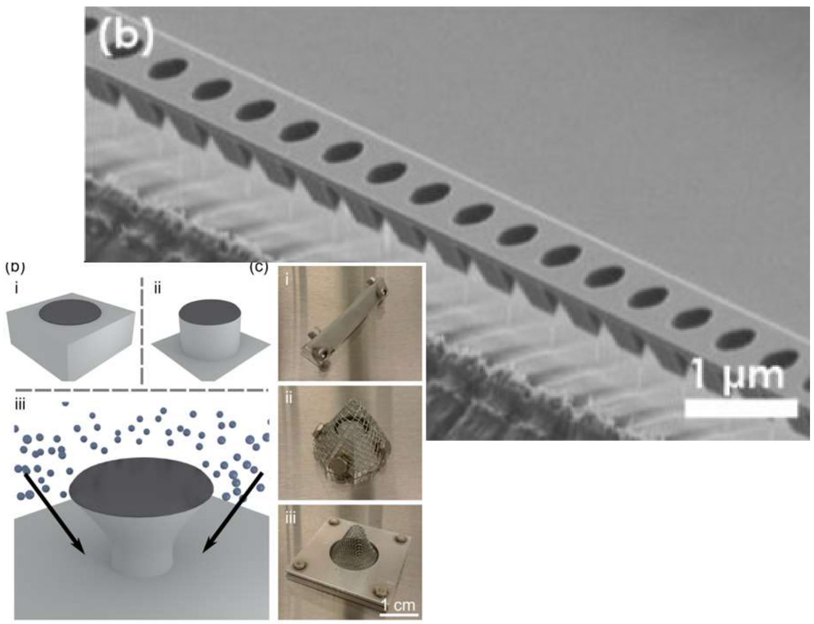
Faraday cage etching



Harvard (Loncar) - 2014

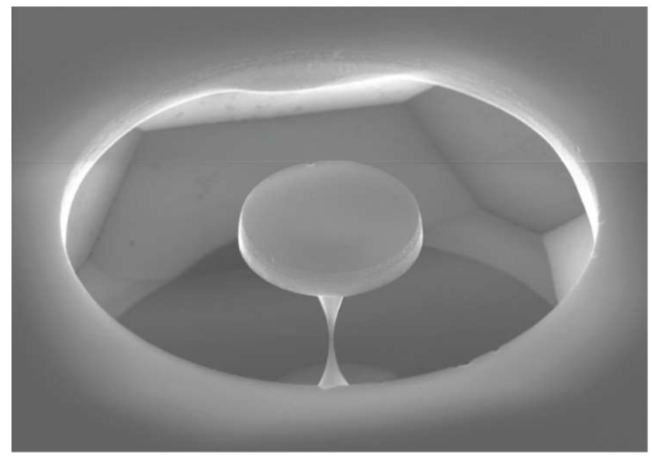
Two new 3D etching techniques

Faraday cage etching



Harvard (Burek/Loncar) - 2014

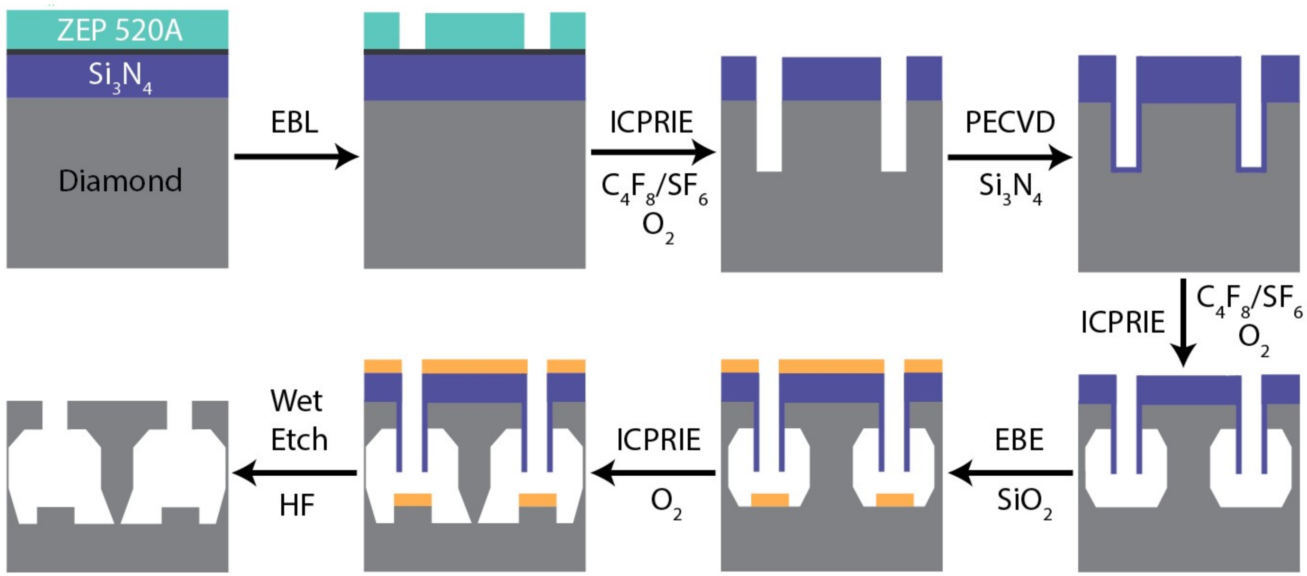
Plasma undercutting



Calgary (Barclay) – 2015

Quasi-isotropic undercut etching

Inspired by silicon **SCREAM** process: Shaw, Zhang, MacDonald, *Micro Electro Mechanical Systems* (1993)



Khanaliloo, Jayakumar, Hryciw, Lake, Kaviani, Barclay, Phys. Rev. X (2015)

Adopted by: Englund (MIT), Vuckovic (Stanford), others …

Quasi-isotropic undercut etching

Key insight:

ELSEVIER

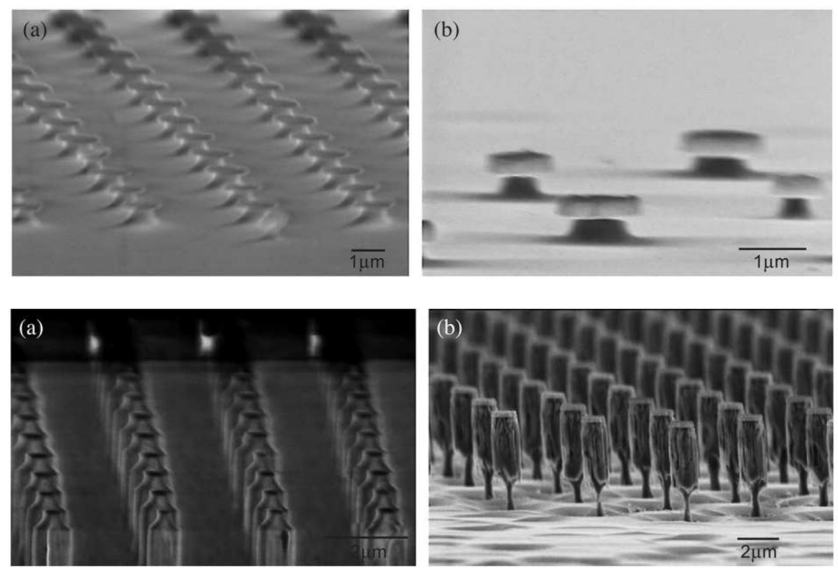
Diamond and Related Materials
Volume 13, Issues 11–12, November–December 2004, Pages 2207-2210

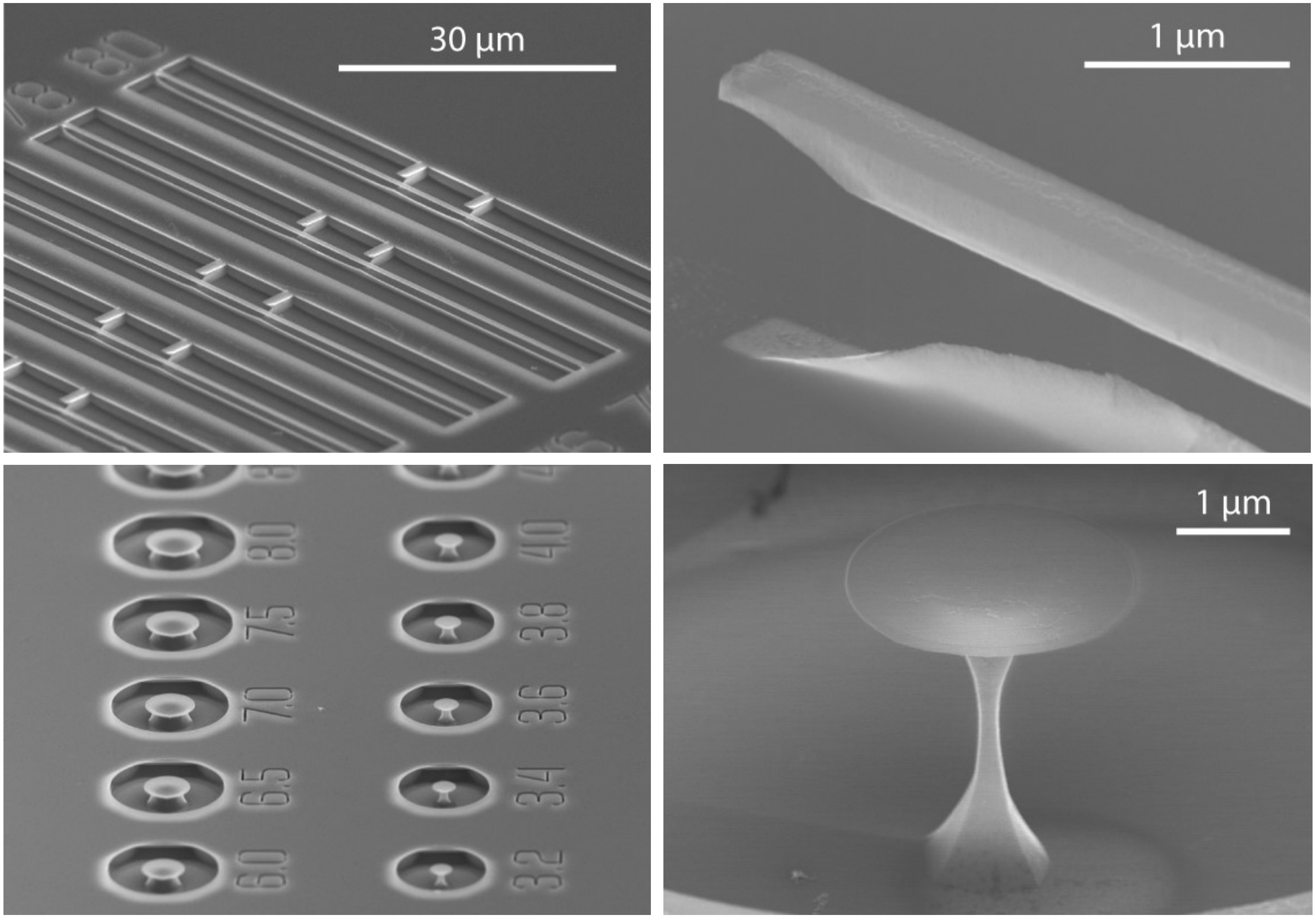
New etching process for device fabrication using diamond

D.S. Hwang, T. Saito, N. Fujimori

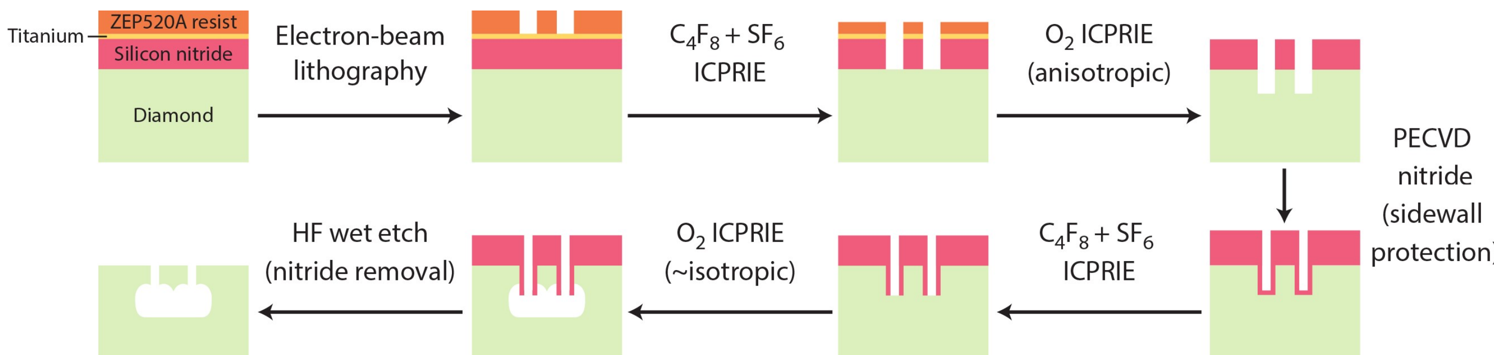
Diamond Research Center, National Institute of Advanced Industrial Science and Technology (AIST), TC2-13, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

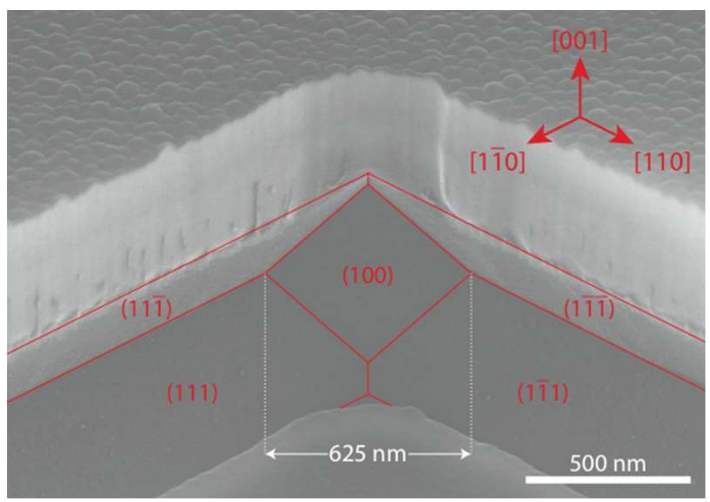
D.S. Hwang et al. / Diamond & Related Materials 13 (2004) 2207–2210



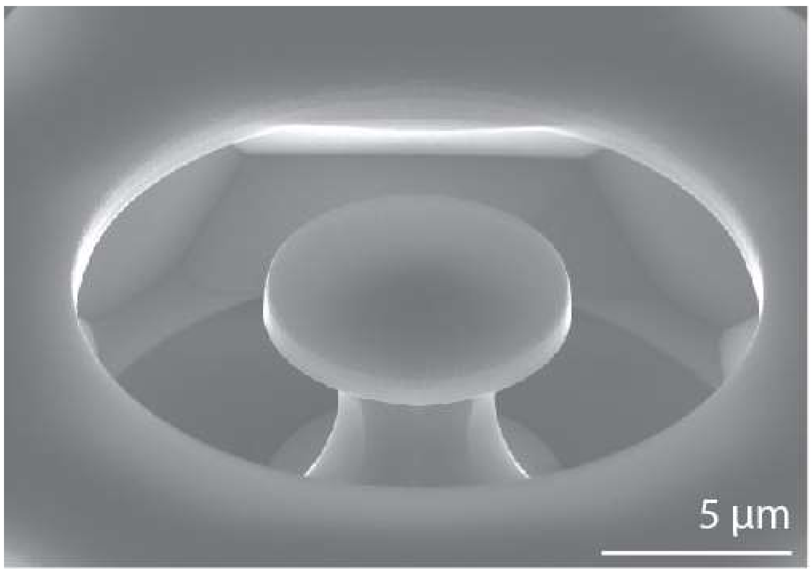

30 µm
1 µm
8.0
7.5
7.0
6.5
6.0
4.0
3.8
3.6
3.4
3.2
1 µm

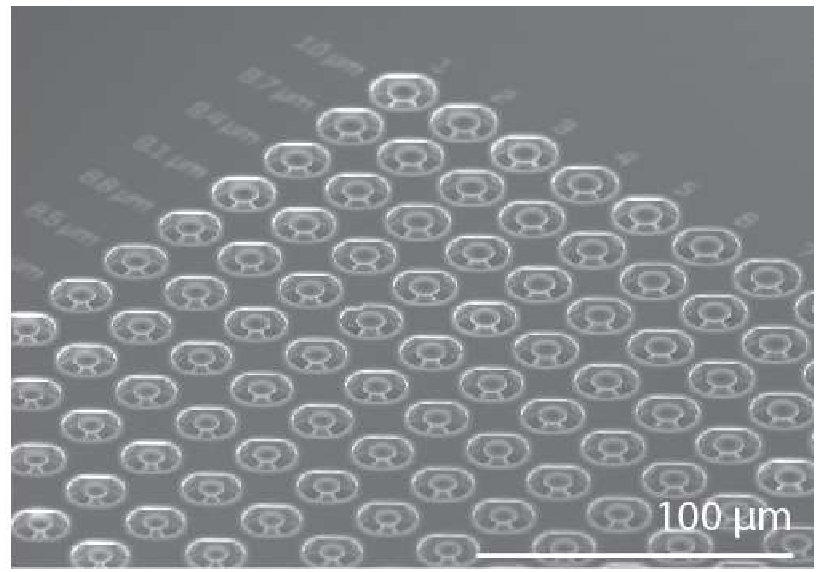
Diamond undercutting





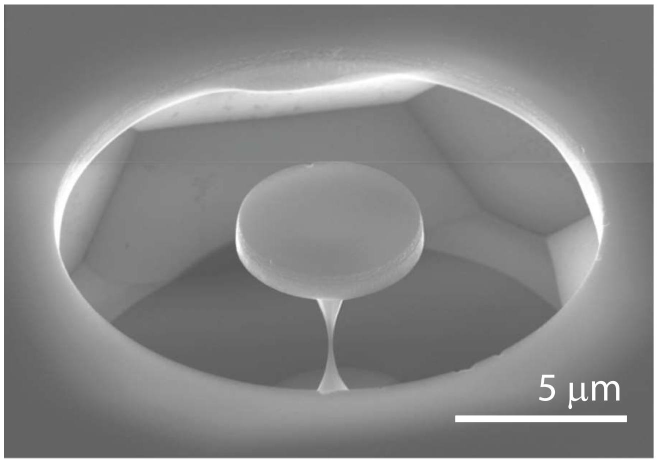
Diamond microdisk cavities

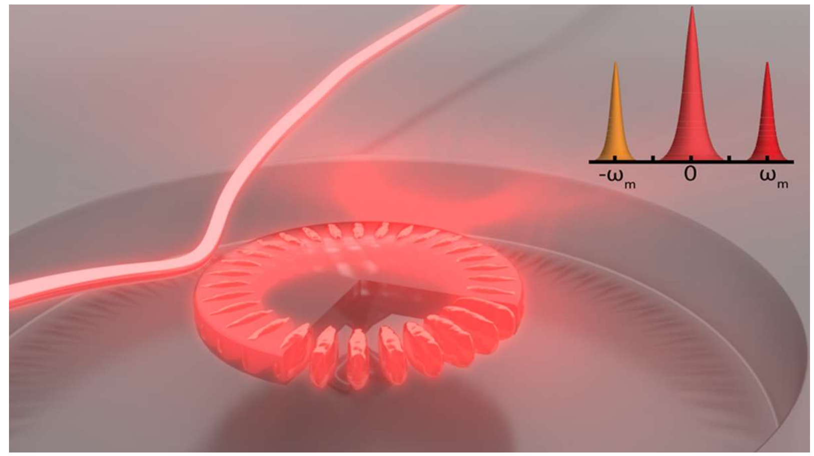


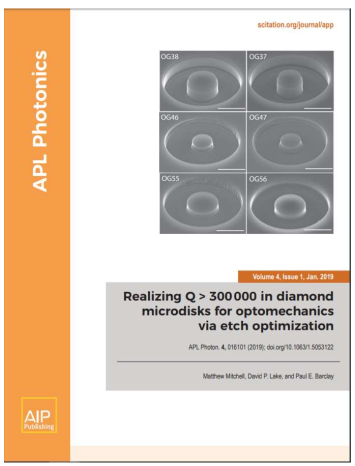


B. Khanaliloo, M. Mitchell, A.C. Hryciw, P.E. Barclay, Nano Letters 15, 5131 (2015)

Diamond microdisk cavities: optics






scitation.org/journal/app

APL Photonics

OG38 OG37 OG46 OG47 OG55 OG56

Volume 4, Issue 1, Jan. 2019

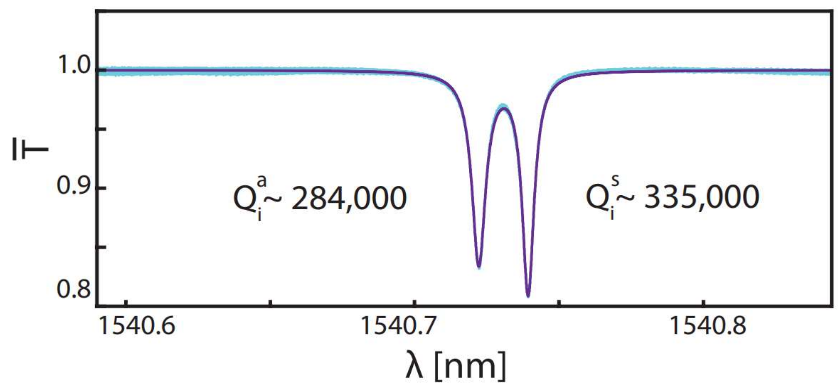
Realizing Q > 300 000 in diamond microdisks for optomechanics via etch optimization

APL Photon. 4, 016101 (2019); doi.org/10.1063/1.5053122

Matthew Mitchell, David P. Lake, and Paul E. Barclay

AIP Publishing

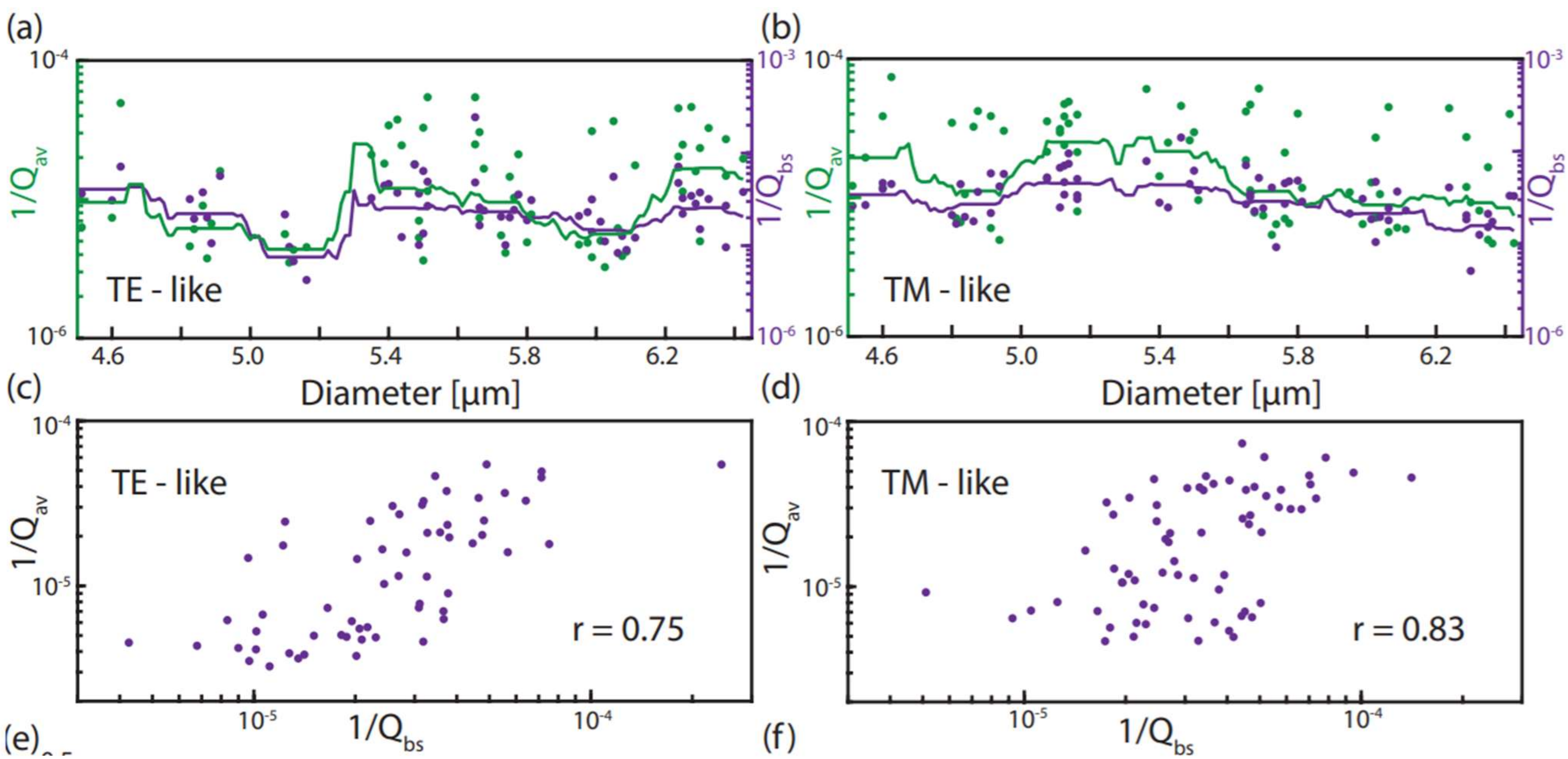
Optical mode spectroscopy: waveguide transmission vs. wavelength



Q > 300,000

Optical loss rate < mechanical frequency

Probing surface roughness



Quantum photonic interfaces: recent advances

Quantum photonics: recent advances

Quantum memory enhanced communication

Experimental demonstration of memory-enhanced quantum communication

https://doi.org/10.1038/s41586-020-2103-5
Received: 19 August 2019
Accepted: 16 January 2020

M. K. Bhaskar[1], R. Riedinger[1], B. Machielse[1], D. S. Levonian[1], C. T. Nguyen[1], E. N. Knall[2], H. Park[1,3], D. Englund[4], M. Lončar[2], D. D. Sukachev[1] & M. D. Lukin[1]✉

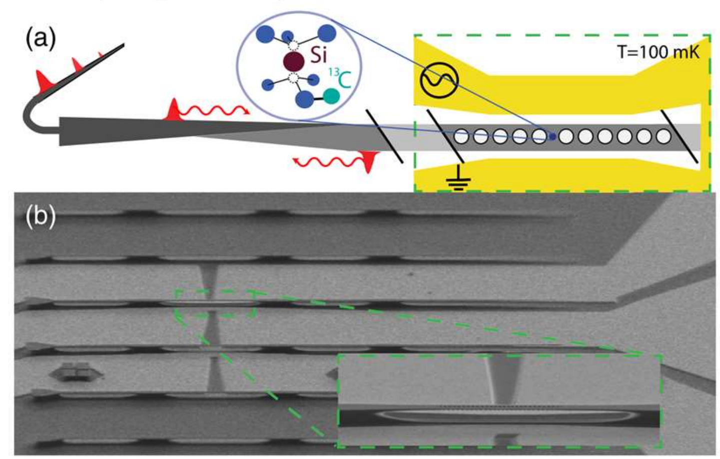
60 | Nature | Vol 580 | 2 April 2020

PHYSICAL REVIEW LETTERS 123, 183602 (2019)

Editors' Suggestion | Featured in Physics

Quantum Network Nodes Based on Diamond Qubits with an Efficient Nanophotonic Interface

C. T. Nguyen,[1] D. D. Sukachev,[1] M. K. Bhaskar,[1] B. Machielse,[1,2] D. S. Levonian,[1] E. N. Knall,[2] P. Stroganov,[1] R. Riedinger,[1] H. Park,[1,3] M. Lončar,[2] and M. D. Lukin[1,*]



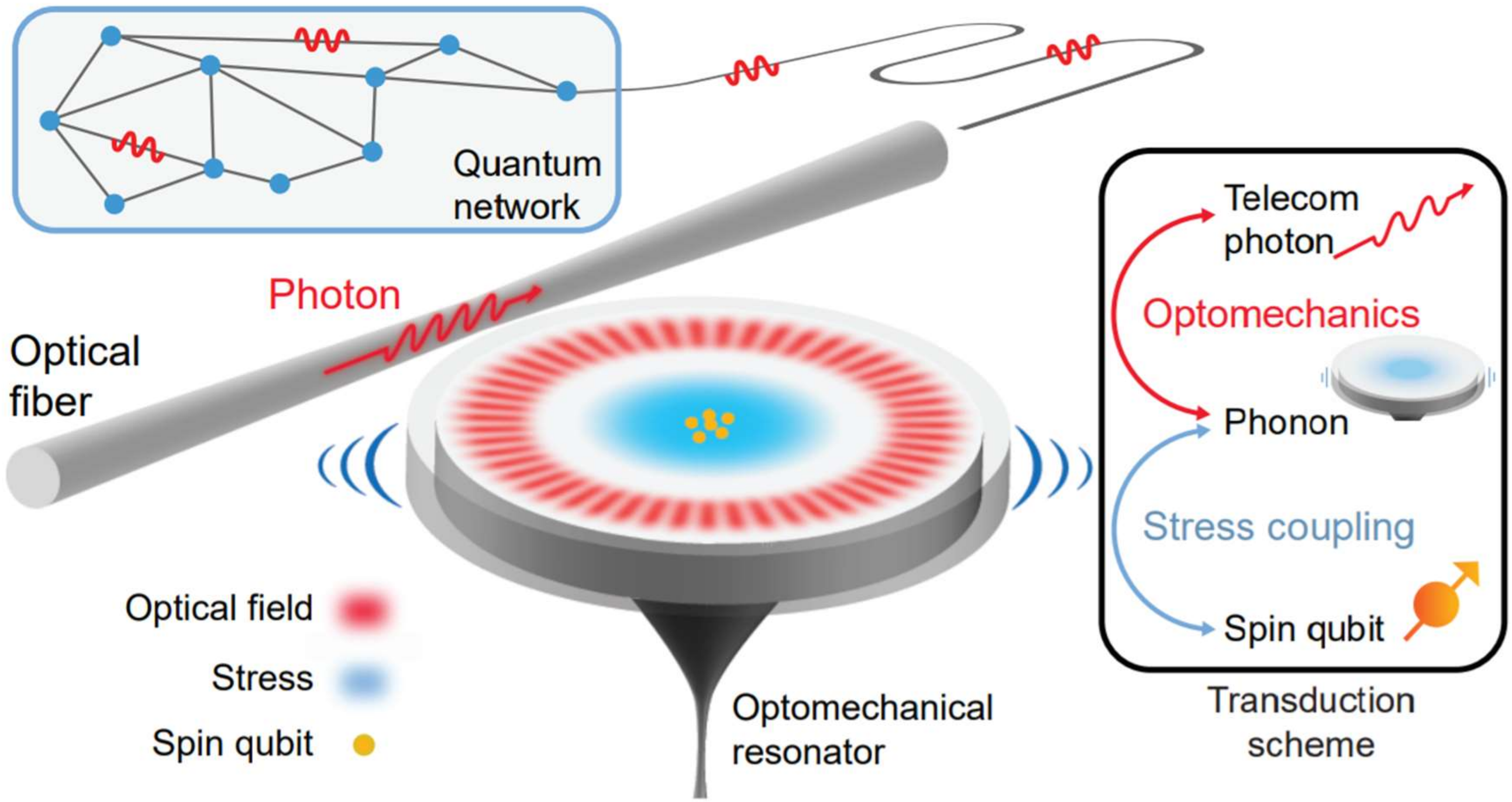
Quantum photonics: recent advances

New qubits:

Defect	Symmetry	ZPL Wavelength	DW Factor (ξ)	Lifetime (τ)	$\hbar\Delta_{GS}/k_b$ [a]
NV	C_{3v}	637 nm	0.03 [118]	11–13 ns [132,184]	N/A
SiV	D_{3d}	737 nm	0.7 [185]	1.6–1.7 ns (4 K) [172,166,176]	2.4 K [135]
GeV	D_{3d}	602 nm	0.6 [169]	6 ns [186]	7.3 K [186]
SnV	D_{3d}	619 nm	0.6 (5 K) [187]	4.5–4.8 ns [137,138]	41 K [167]
PbV	D_{3d} [b]	520–552 nm [188,189]	unknown	> 3 ns [188,189]	200–270 K [188,189]
SiV0	D_{3d}	946 nm	0.9 [103]	1.8 ns [103]	N/A

Janitz et al., Optica **7**, 1232 (2020)

Diamond spins + optomechanics



The emergence of quantum phononics

Question: can **phonons** be used to process information?

Ion trap quantum computers

PHYSICAL REVIEW A, VOLUME 62, 022311

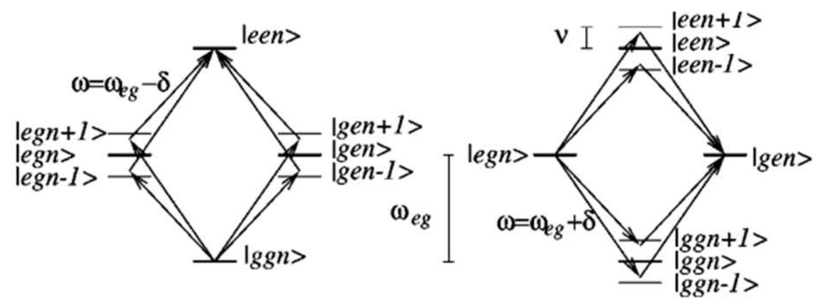
Entanglement and quantum computation with ions in thermal motion

Anders Sørensen and Klaus Mølmer
Institute of Physics and Astronomy, University of Aarhus, DK-8000 Århus C, Denmark

(Received 10 February 2000; revised manuscript received 1 May 2000; published 18 July 2000)

With bichromatic fields, it is possible to deterministically produce entangled states of trapped ions. In this paper we present a unified analysis of this process for both weak and strong fields, for slow and fast gates. Simple expressions for the fidelity of creating maximally entangled states of two or an arbitrary number of ions under nonideal conditions are derived and discussed.

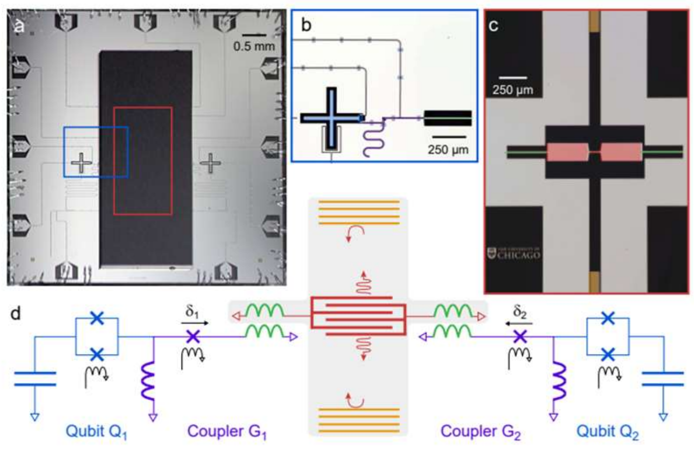
PACS number(s): 03.67.Lx, 03.65.Bz, 89.70.+c



The emergence of quantum phononics

Question: can phonons be used to process information?

Qubit entanglement

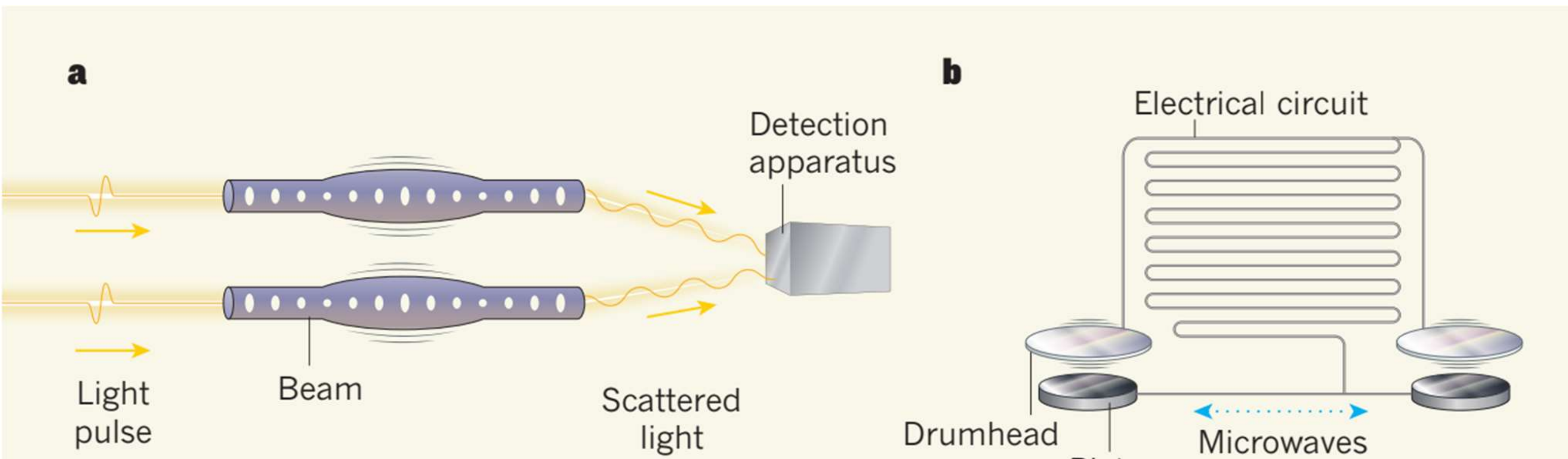


Bienfait, Cleland et al. Science 364, 368 (2019)

The emergence of quantum phononics

Question: can phonons be used to process information?

Entanglement of “massive” mechanical resonators



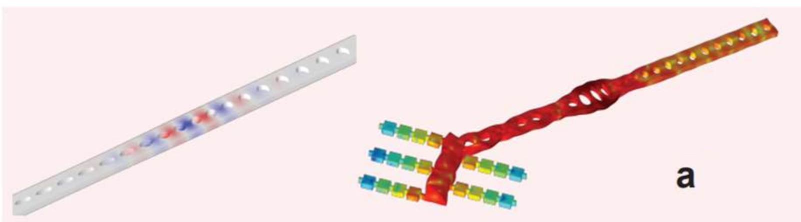
From News and Views by Andrew Armour

Riedinger et al. and Ockeloen–Korppi et al. Nature 556 (2018)

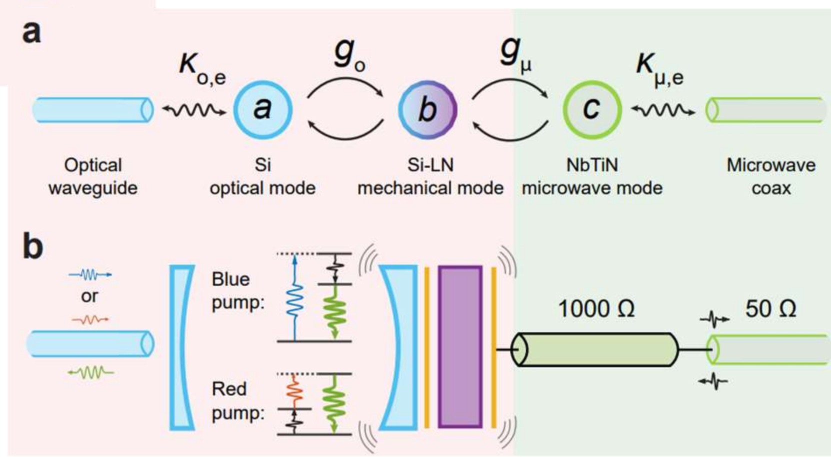
The emergence of quantum phononics

Question: can phonons be used to process information?

Microwave to optical photon entanglement – networking superconducting QC



Jiang, Mayor, Safavi-Naeni et al. arxiv:2210.10739



Also see: Lehnert/Regal, Painter

Phonons and solid-state qubits

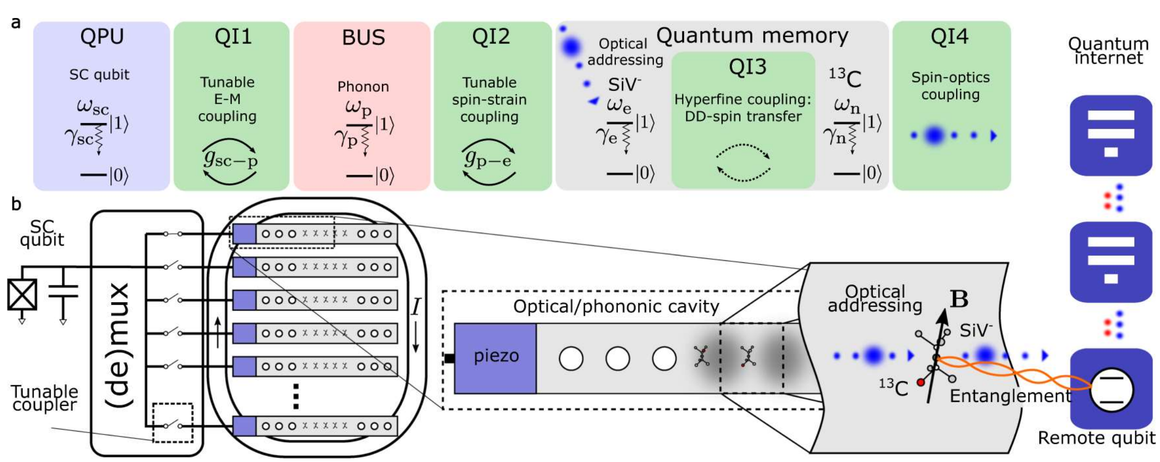
Quantum interconnects

Article | Open Access | Published: 04 August 2021

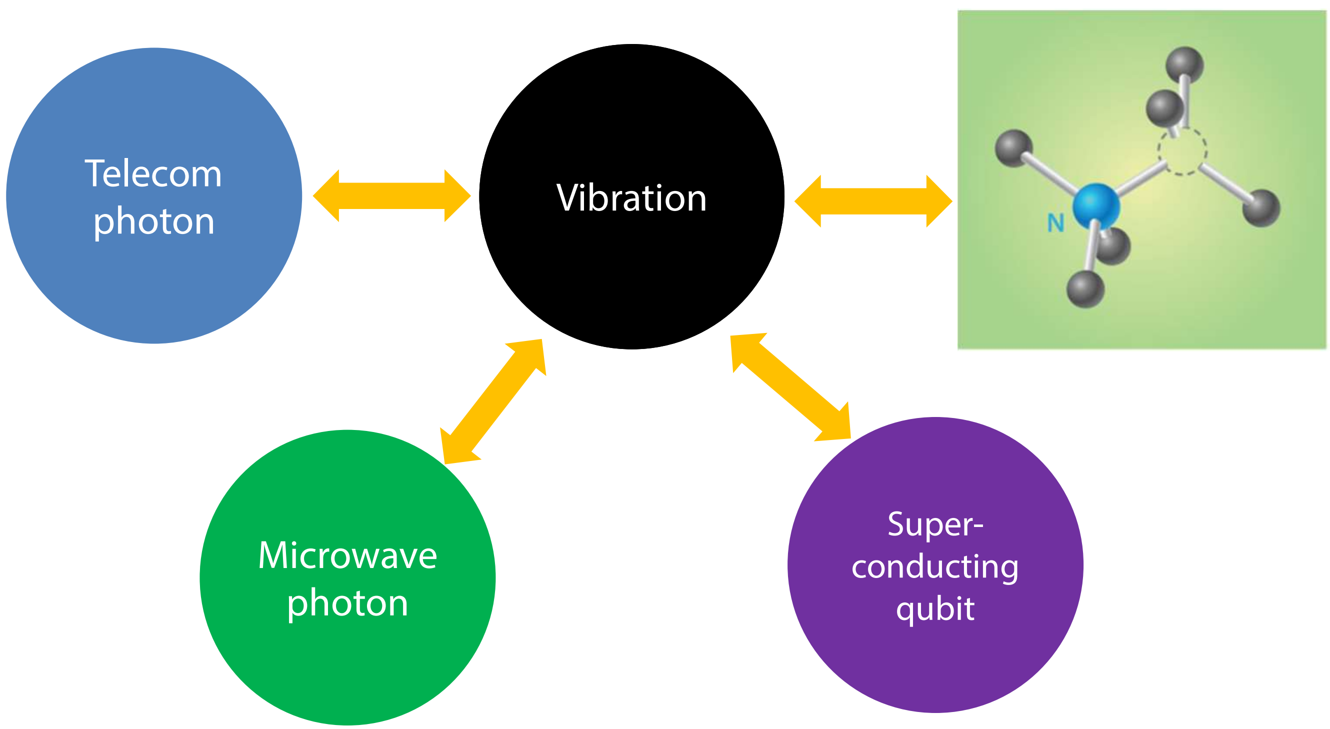
A phononic interface between a superconducting quantum processor and quantum networked spin memories

Tomáš Neuman, Matt Eichenfield, Matthew E. Trusheim, Lisa Hackett, Prineha Narang & Dirk Englund

npj Quantum Information **7**, Article number: 121 (2021) | Cite this article

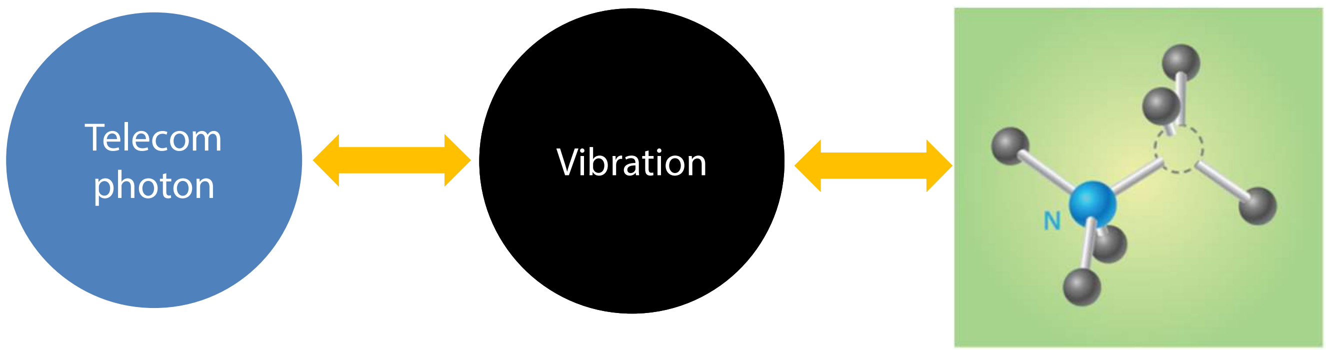


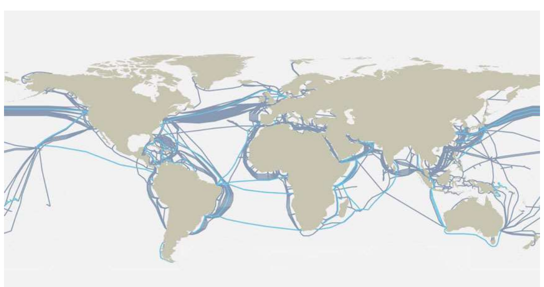
Harnessing phonons: translating quantum information



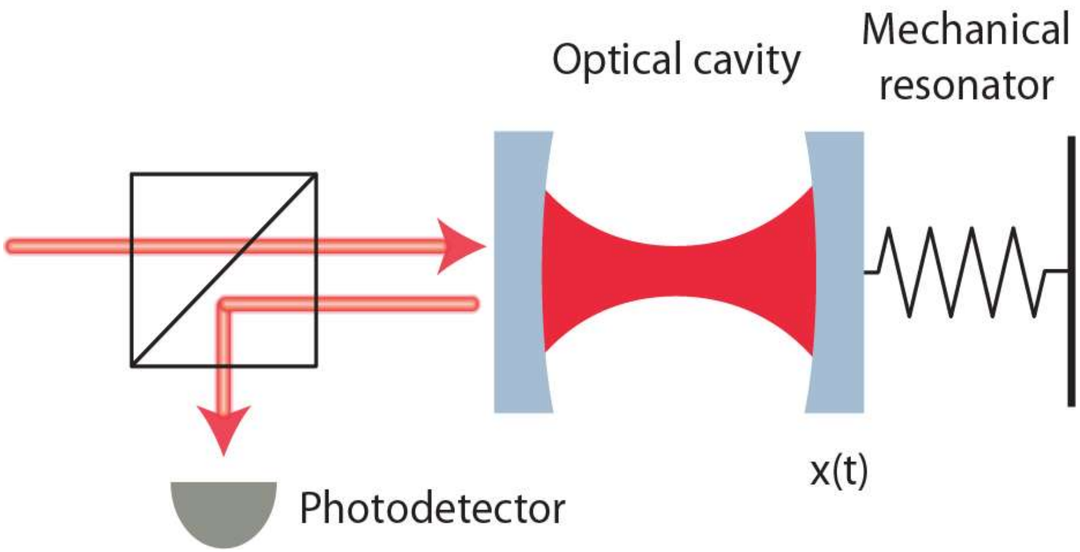
Hybrid quantum interface: optomechanical spin control

Controlling diamond quantum memories with telecom photons





Cavity optomechanics



Photons transfer momentum to mirror, and vice versa

Strength of interaction is enhanced in nanoscale devices

Cavity optomechanics

Zoology of cavity optomechanical systems

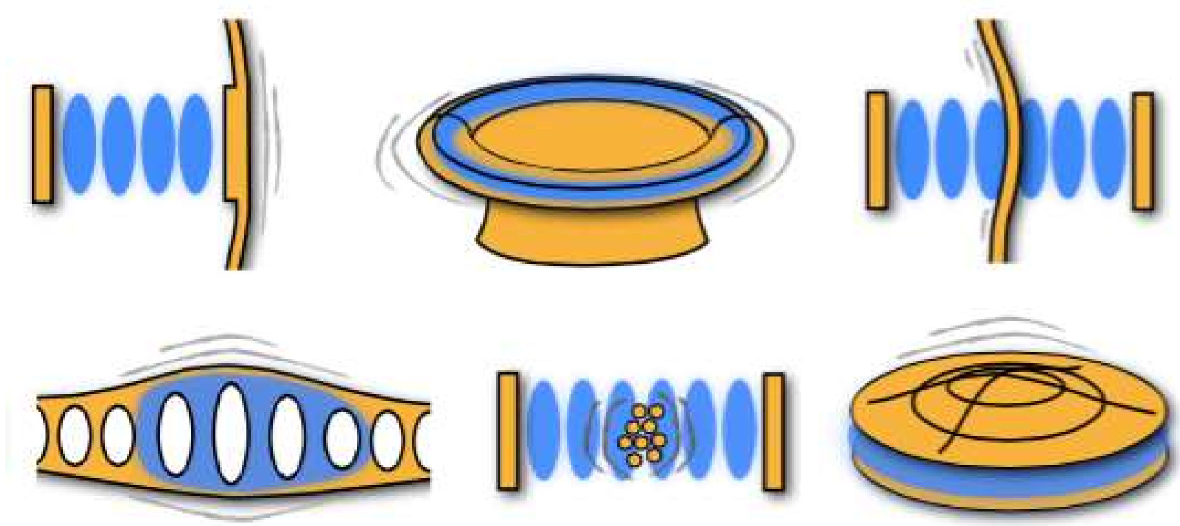


Image from Florian Marquardt – MPQ / Universität Erlangen/Nürnberg

Diamond: ultimate optomechanical material?

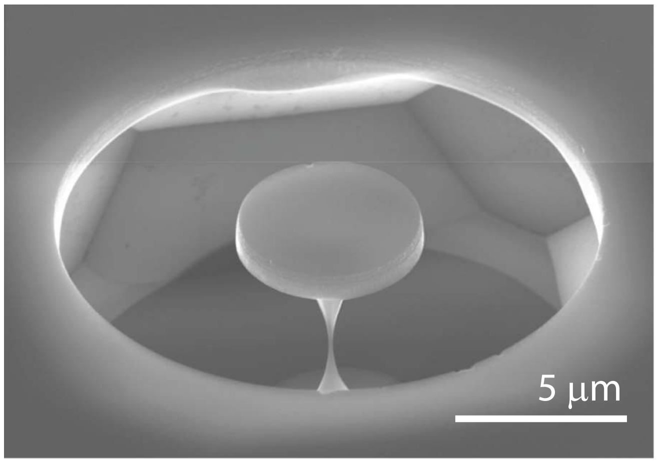
CVD grown
Can be ultrapure (< 1ppb)

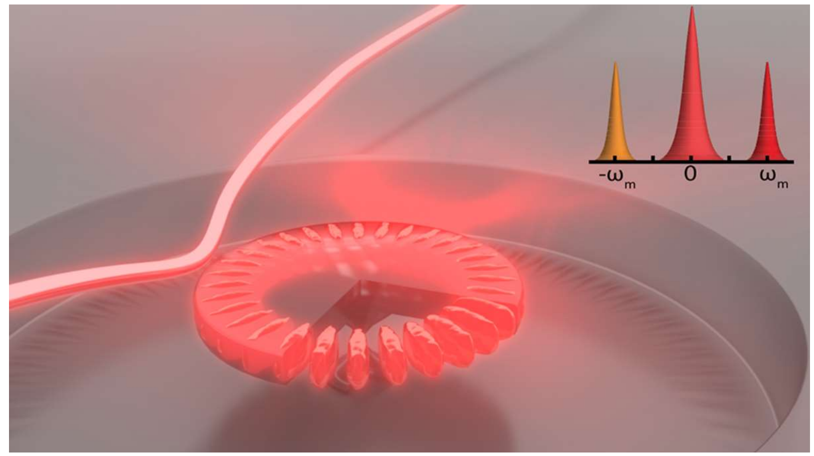
Available commercially
e.g. Element Six (UK)

Unmatched mechanical properties: low mechanical dissipation
Large transparency window: low optical dissipation
No two photon absorption: large field intensity

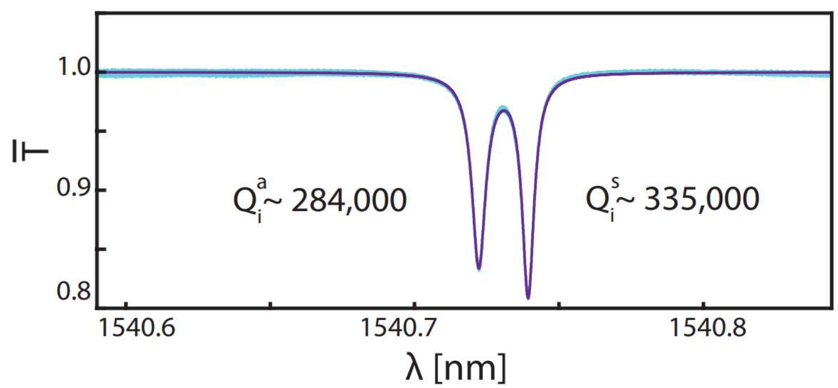
Potential for large optomechanical cooperativity

Diamond microdisk cavities: optics





Optical mode spectroscopy: waveguide transmission vs. wavelength

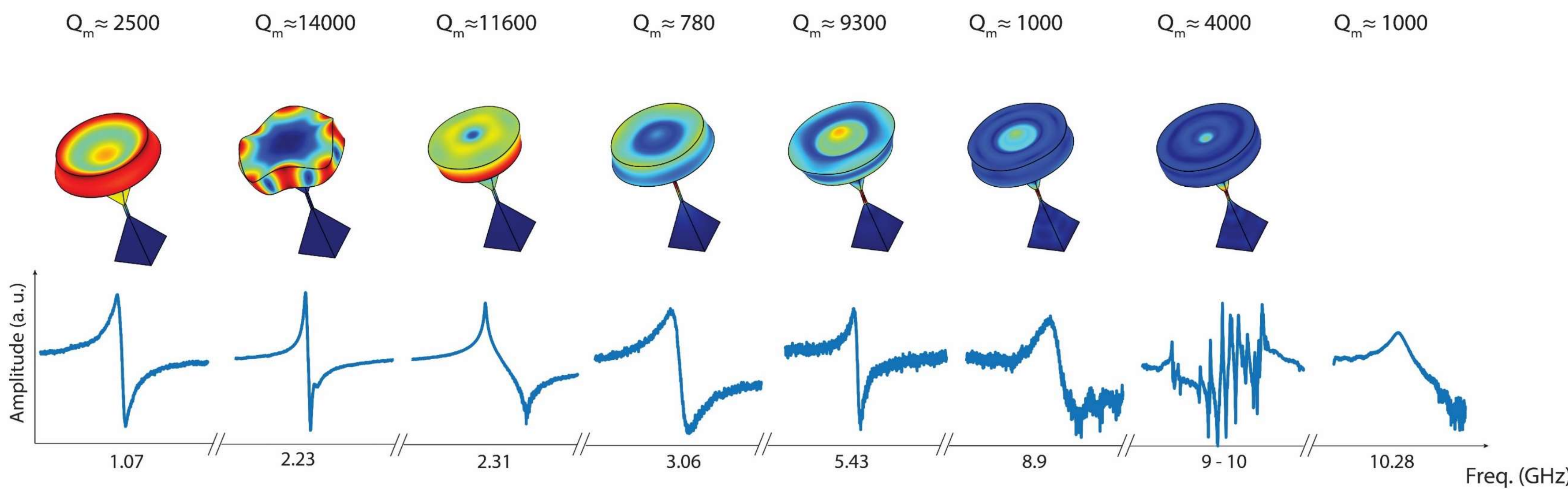


Q > 300,000

Optical loss rate < mechanical frequency

Mitchell et al. Optica (2016) and APL Photonics (2021)

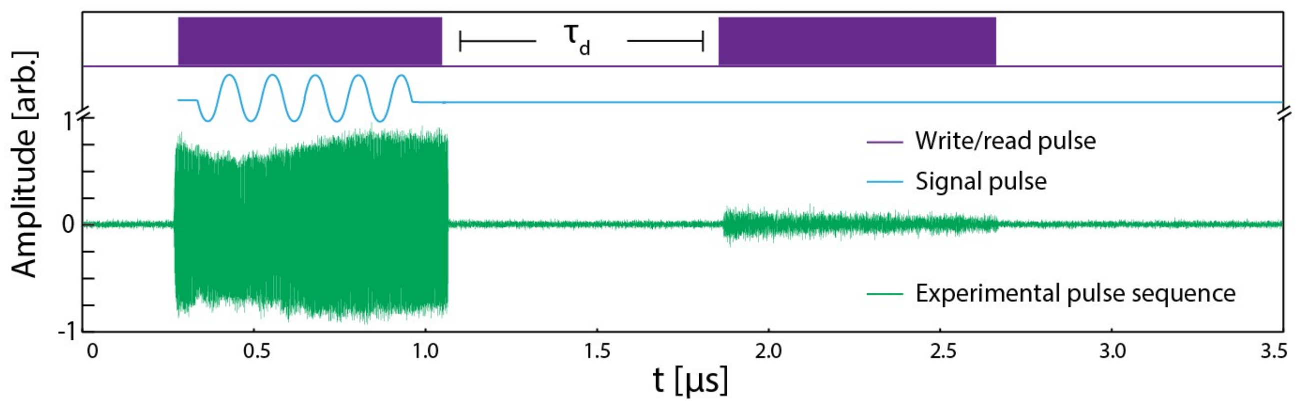
Diamond optomechanics



Behjat et al.

Optomechanical pulse storage

Photon-phonon conversion > optical and mechanical dissipation



Transfer signal from optical to mechanical domain

Store in mechanical oscillation

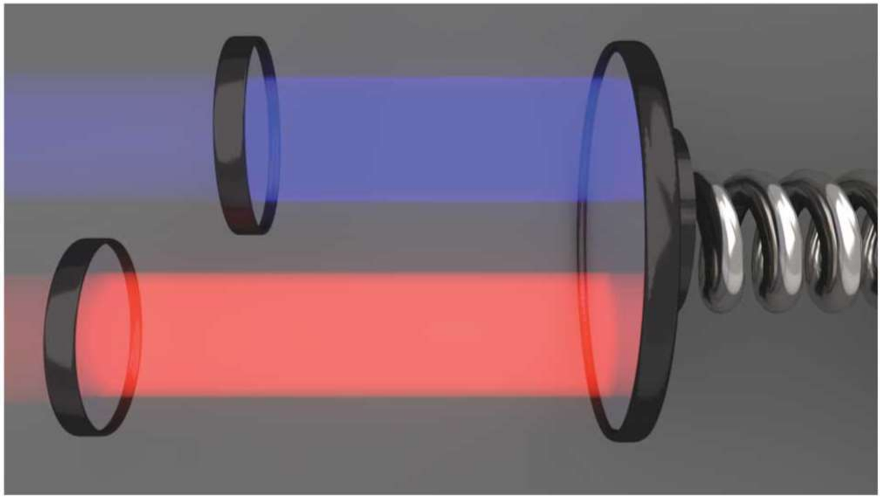
Readout optically

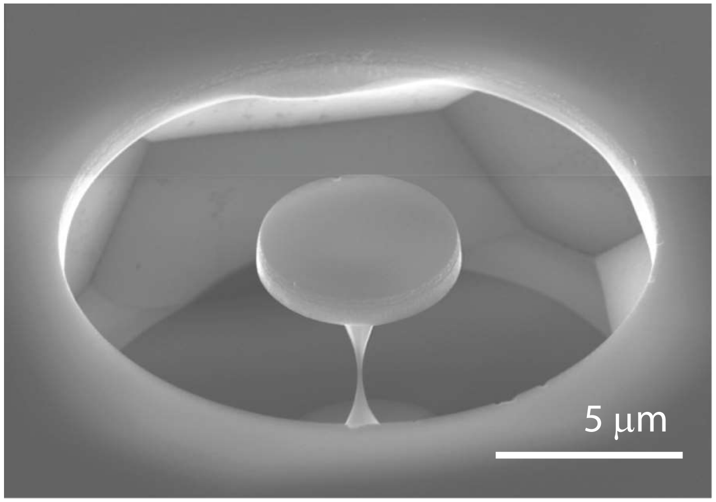
Lake, Mitchell, Sukachev, Barclay, Nature Communications (2021)

Also see: work from Hailin Wang (Oregon), Sussman (NRC Ottawa)

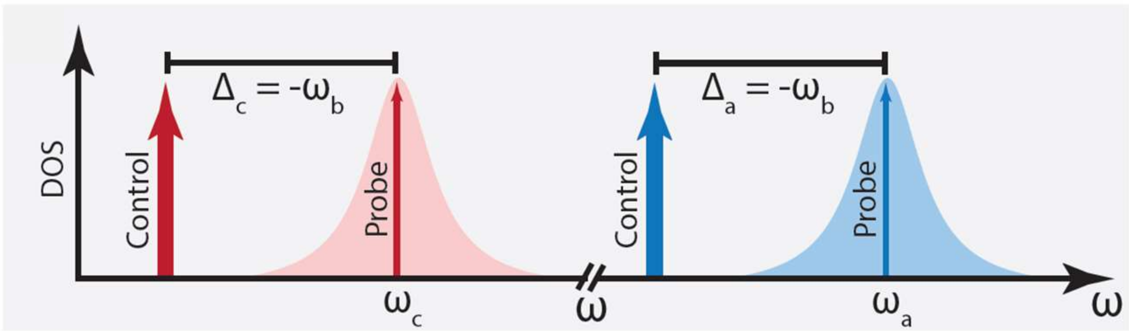
Coherent phonon-photon interactions

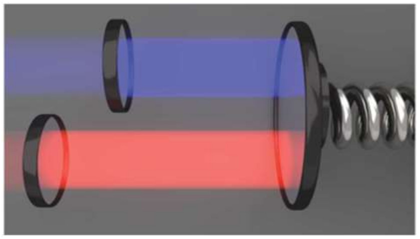
Creating photon-phonon-photon interactions

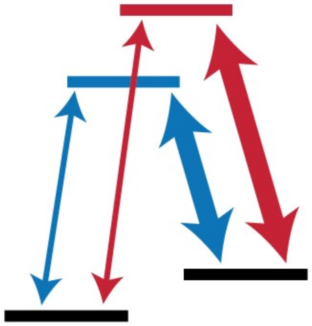




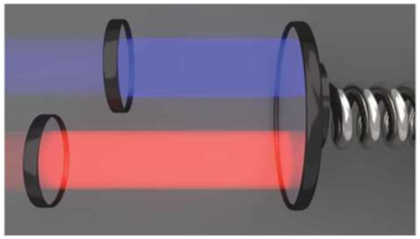
Optomechanically induced transparency



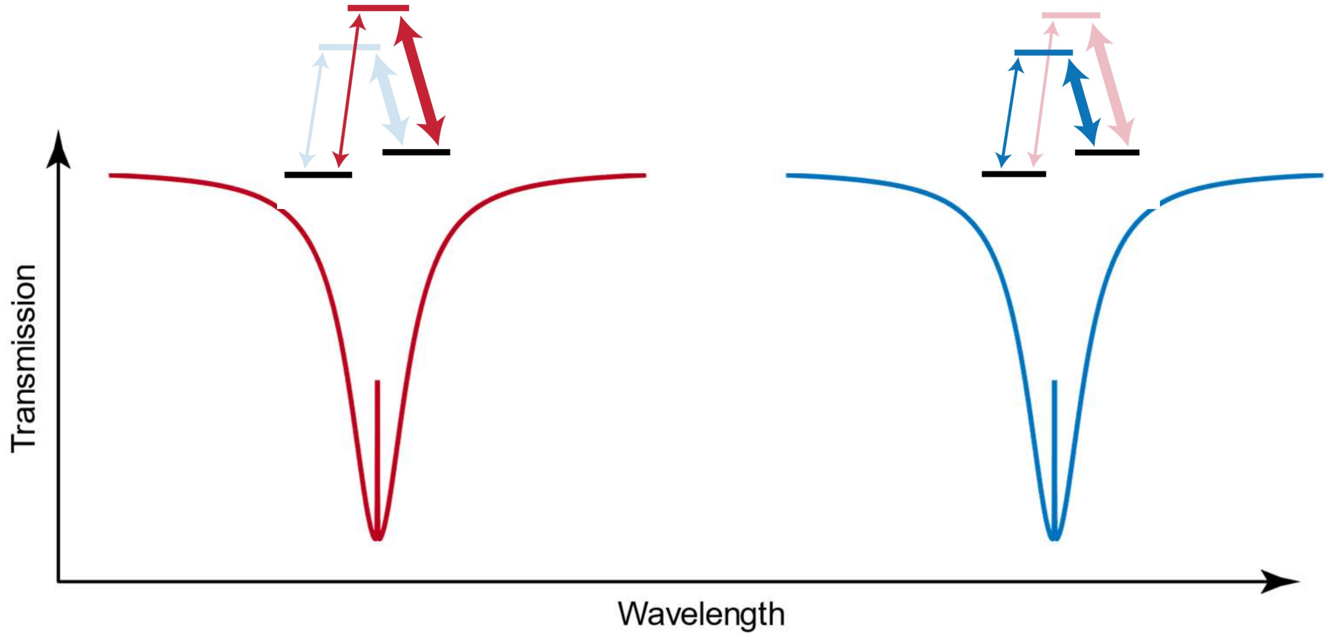




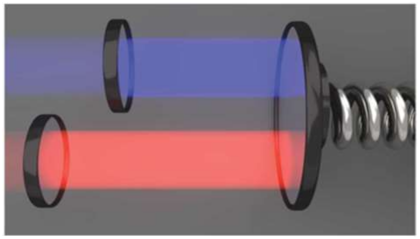
Double OMIT



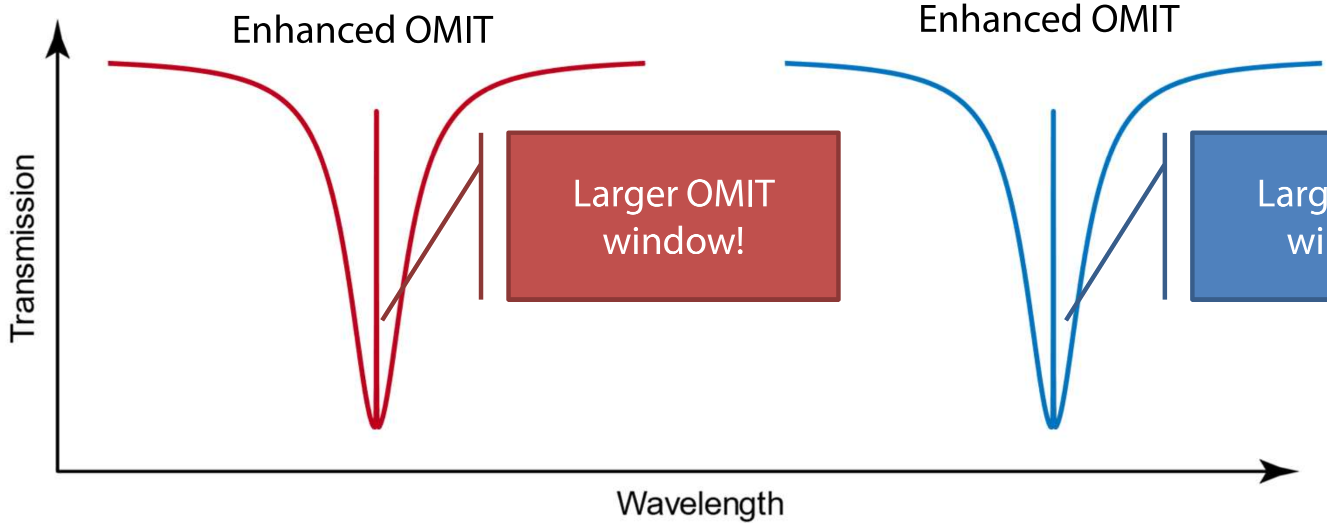
No coupling:

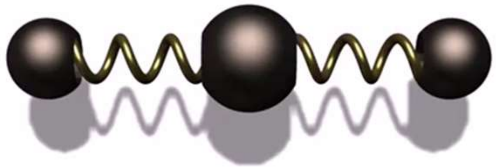


Double OMIT

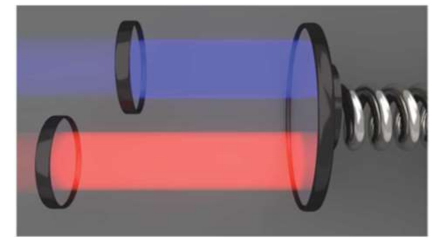


In phase input fields:

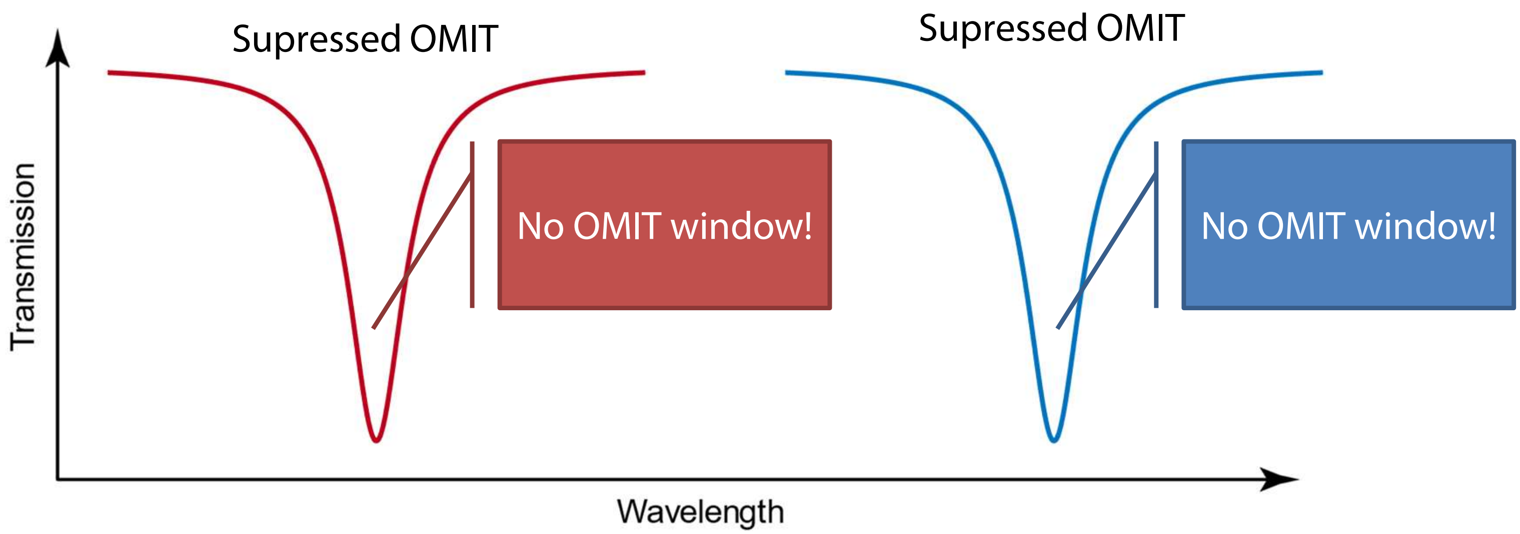


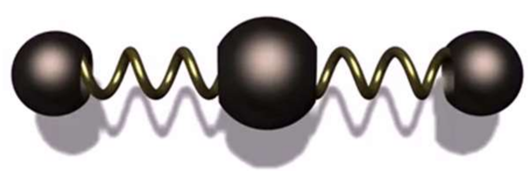


Double OMIT



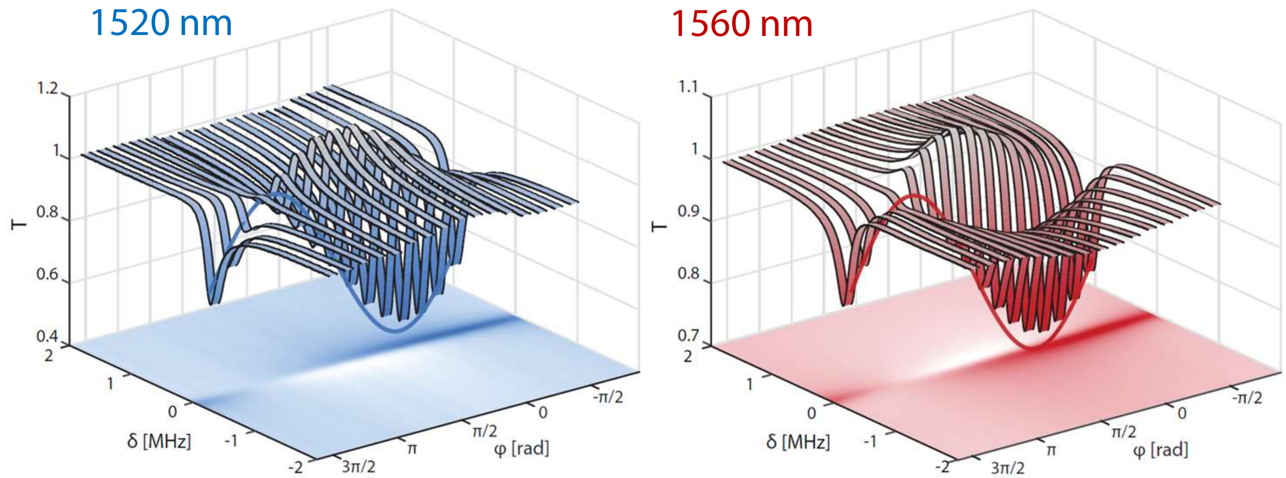
Out of phase input fields:

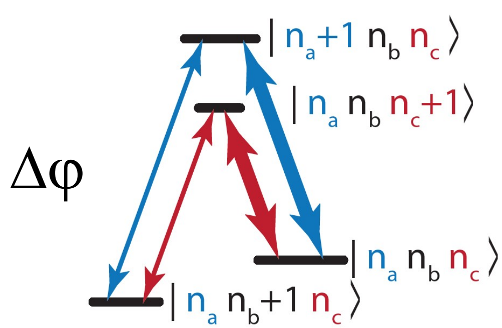




Double OMIT

Response of blue and red probes is sensitive to their relative phase





$\Delta\varphi$: phase difference between red/blue paths

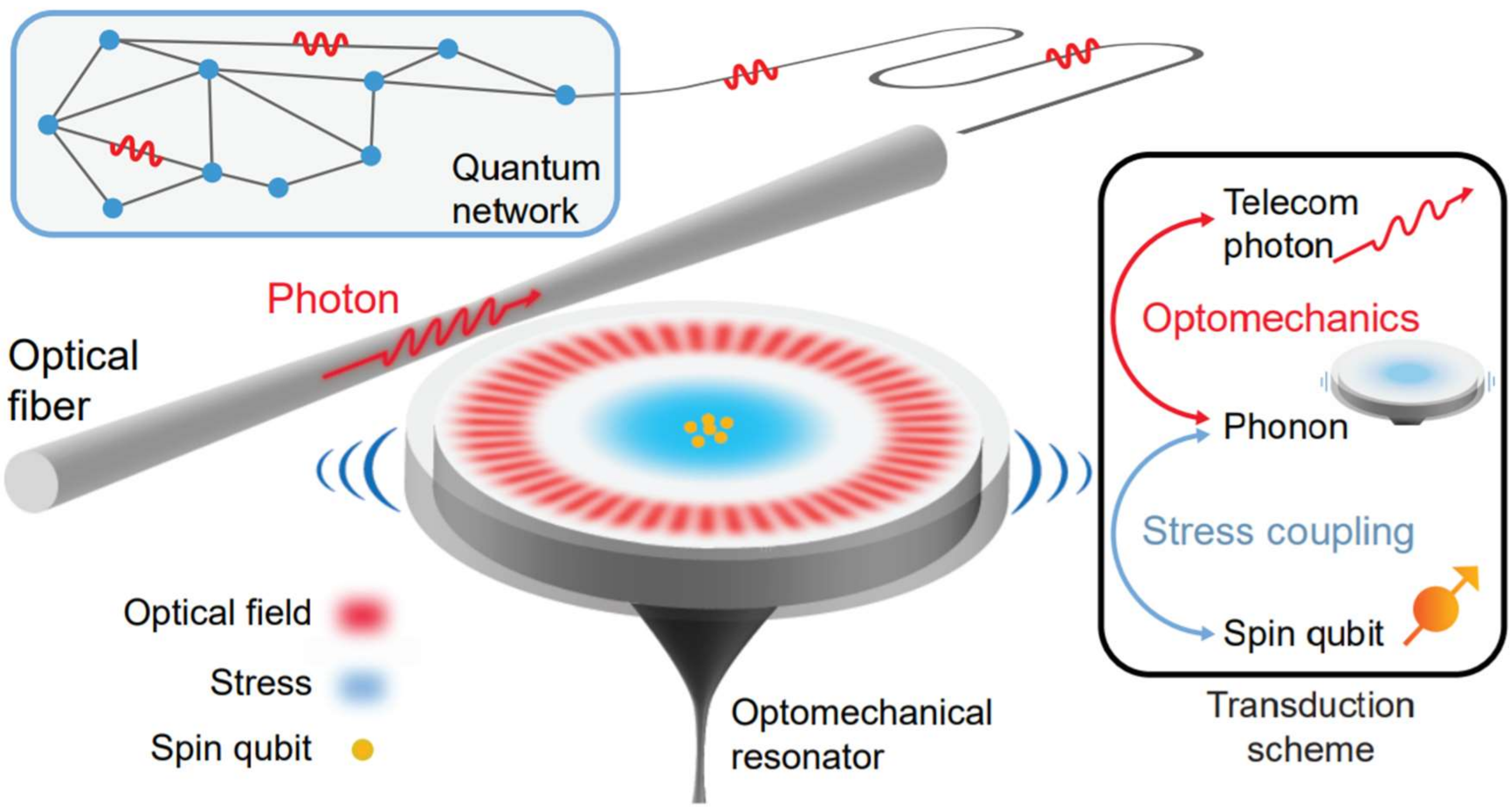
If $\Delta\varphi = \pi$: excite mechanical "dark mode"

Lake et al., Nature Communications 2020

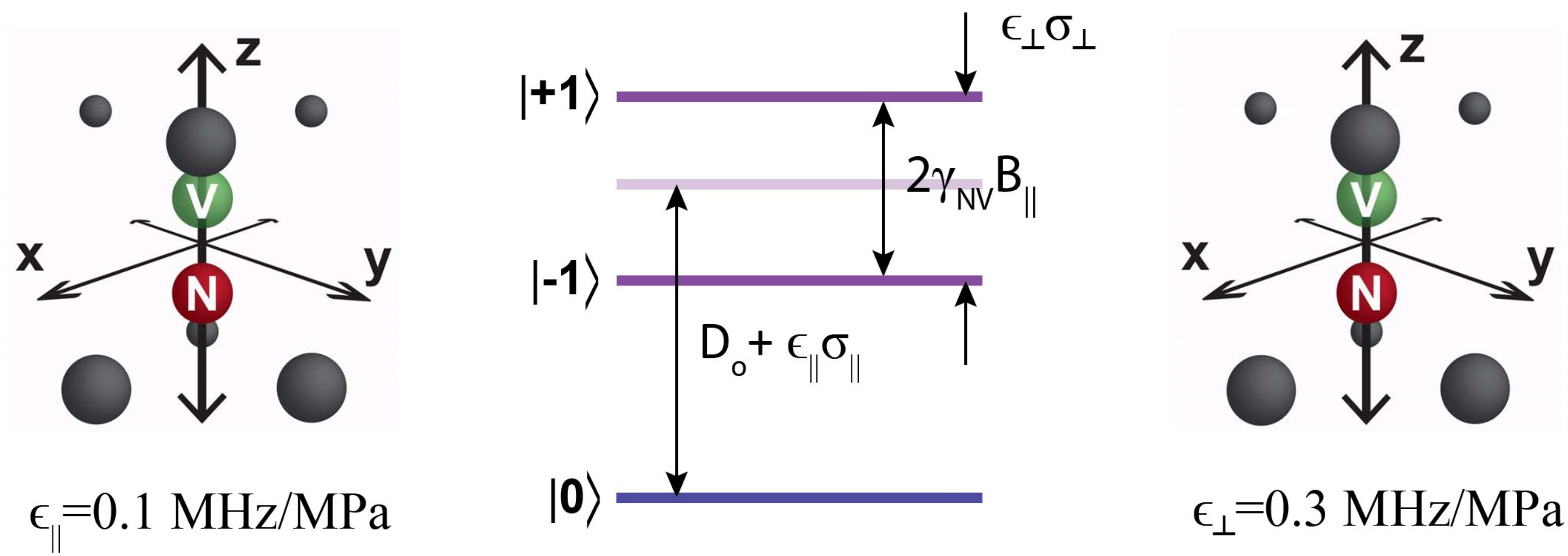
Diamond optomechanics: summary

Can coherently control GHz mechanical resonances
using optical fields

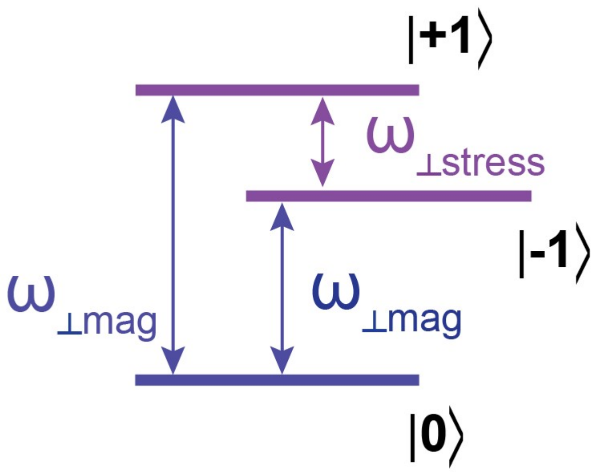
Spin-optomechanics

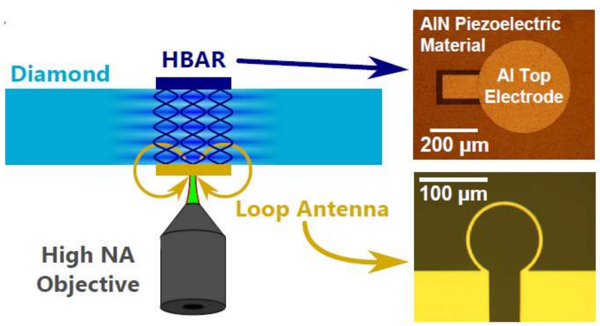


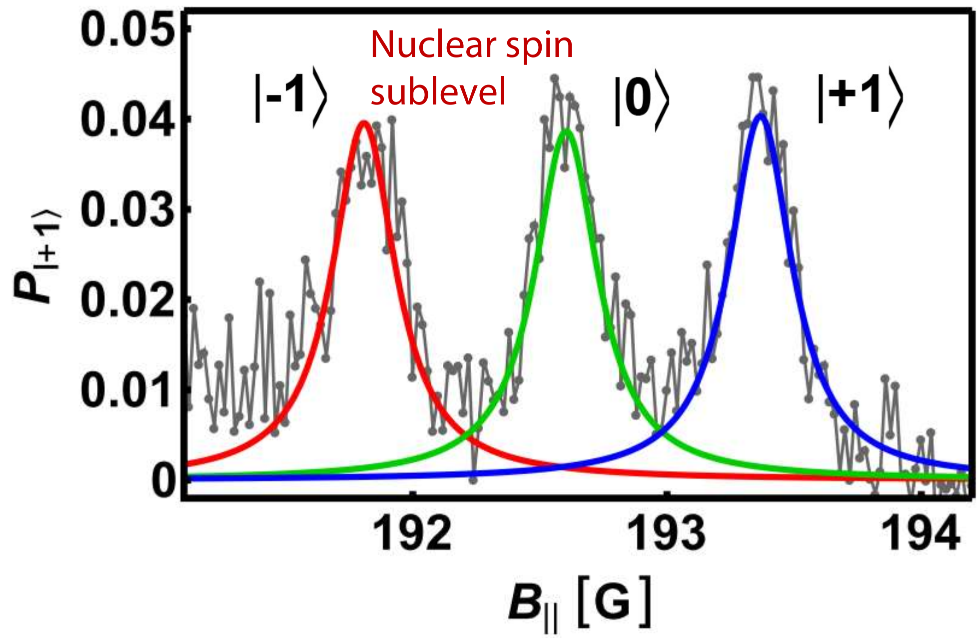
Lattice strain in NV centres



Mechanical driving of NV spin: early work



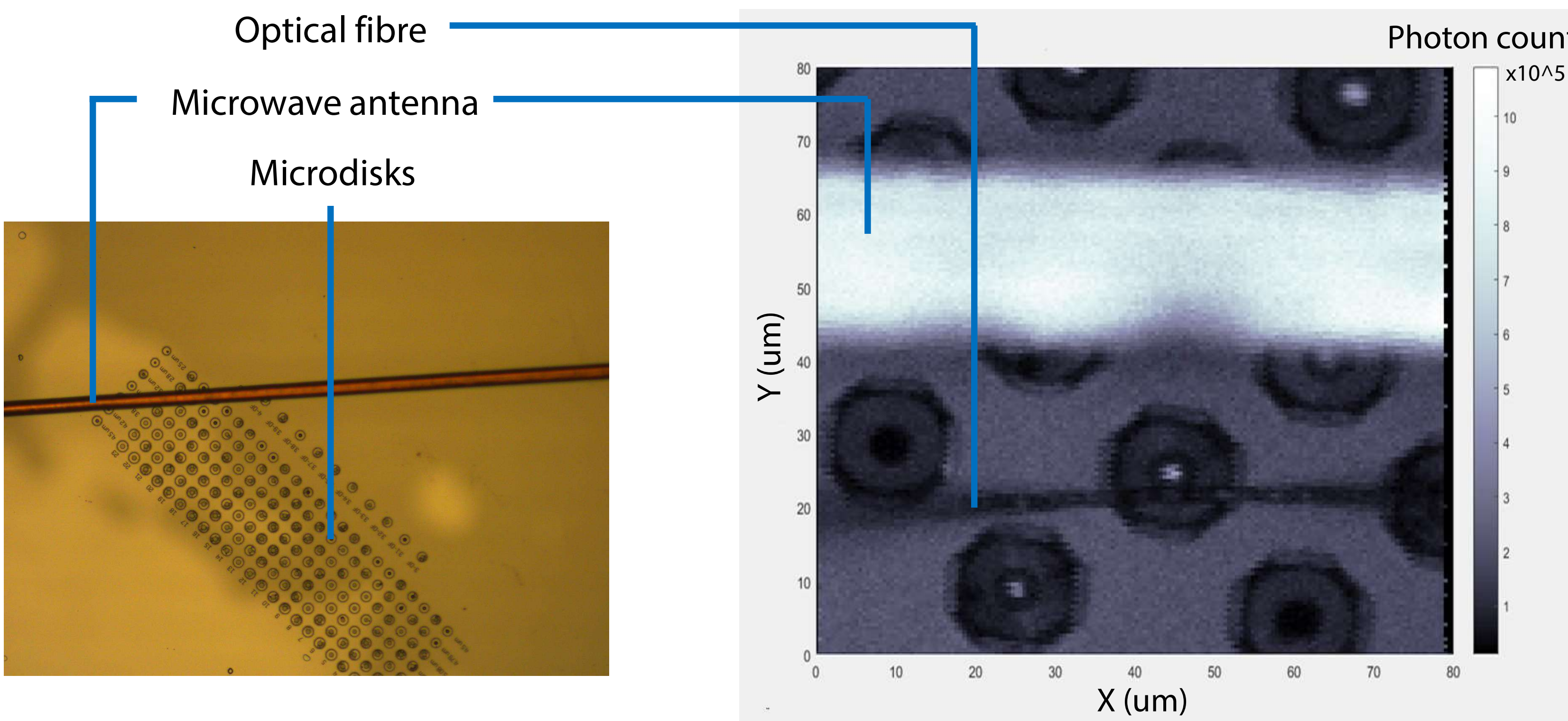




MacQuarrie, Bhave, Fuchs et al., “Mechanical spin control of nitrogen-vacancy centers in diamond,” Physical Review Letters **111**, 227602 (2013)

Also: Jayich (UCSB), Malentinsky (Basel) and Wang (Oregon)

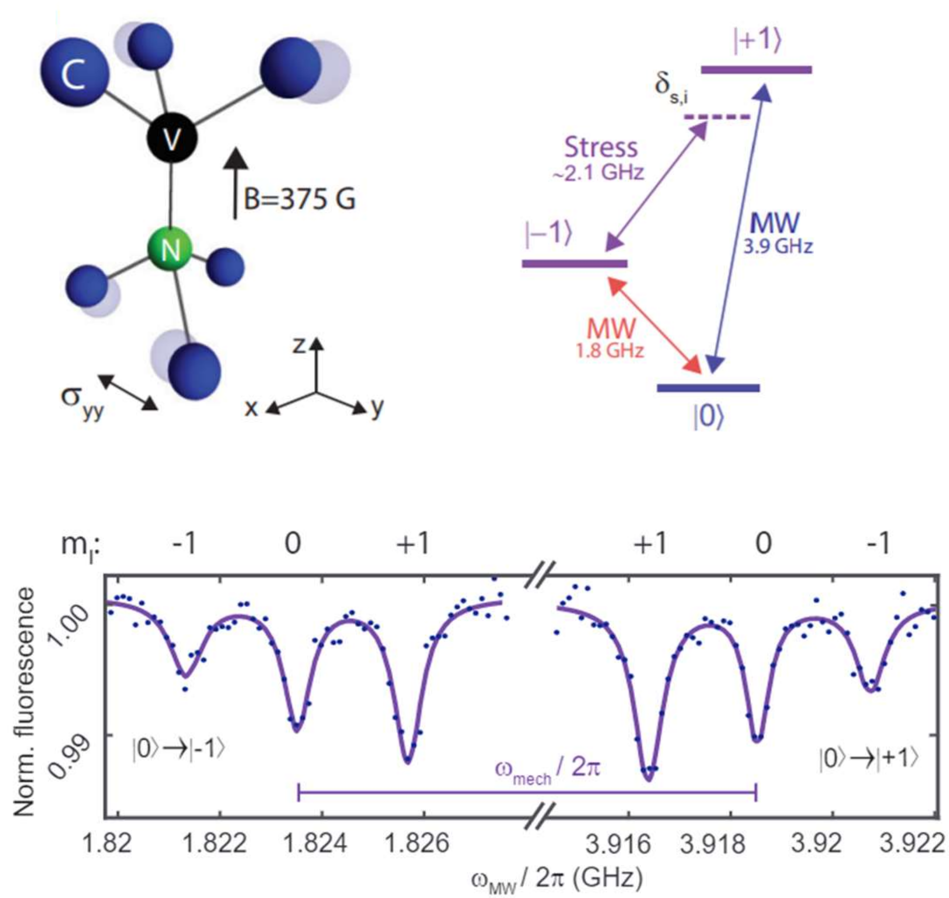
Optomechanical spin control: setup



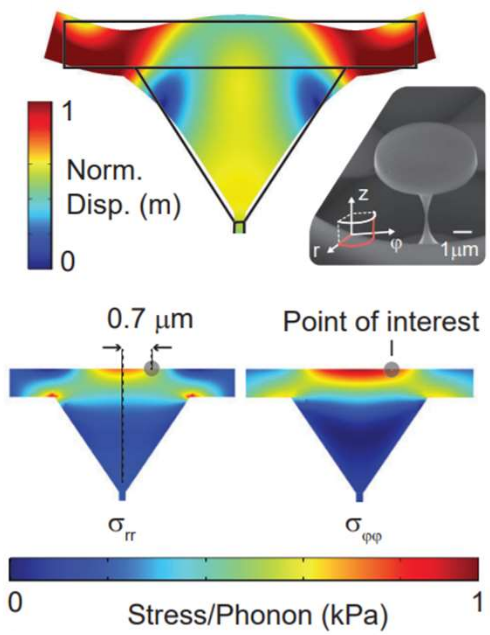
Optical microscope image

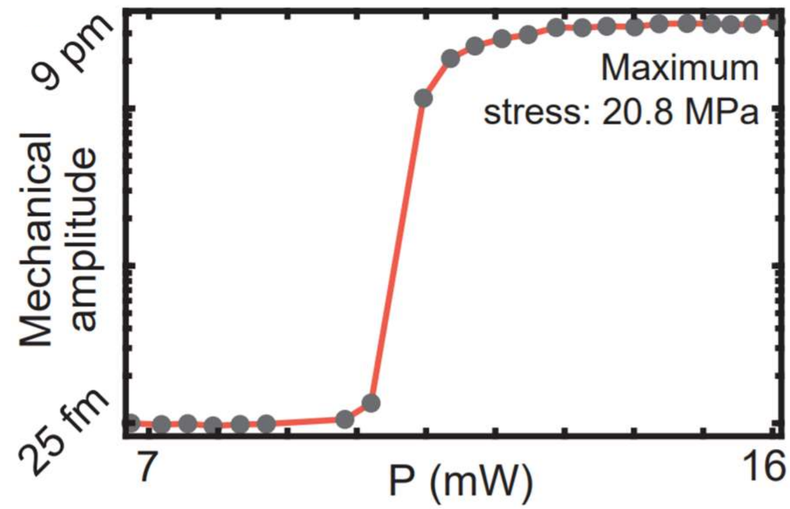
Photoluminescence scan

NV ensemble spin properties



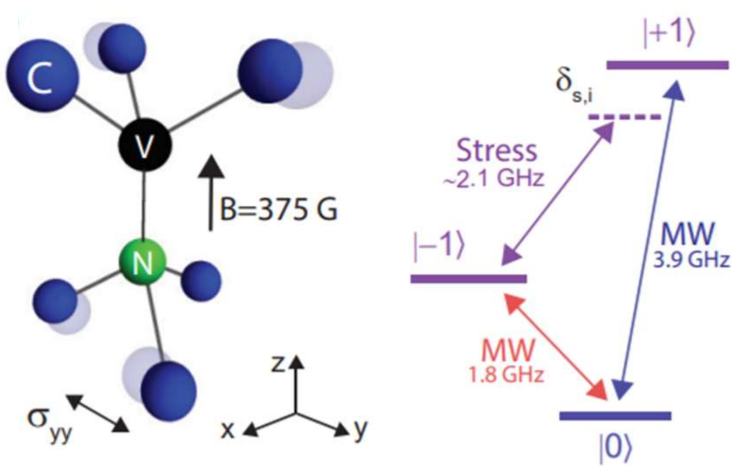
Optomechanical spin control: phonon driving



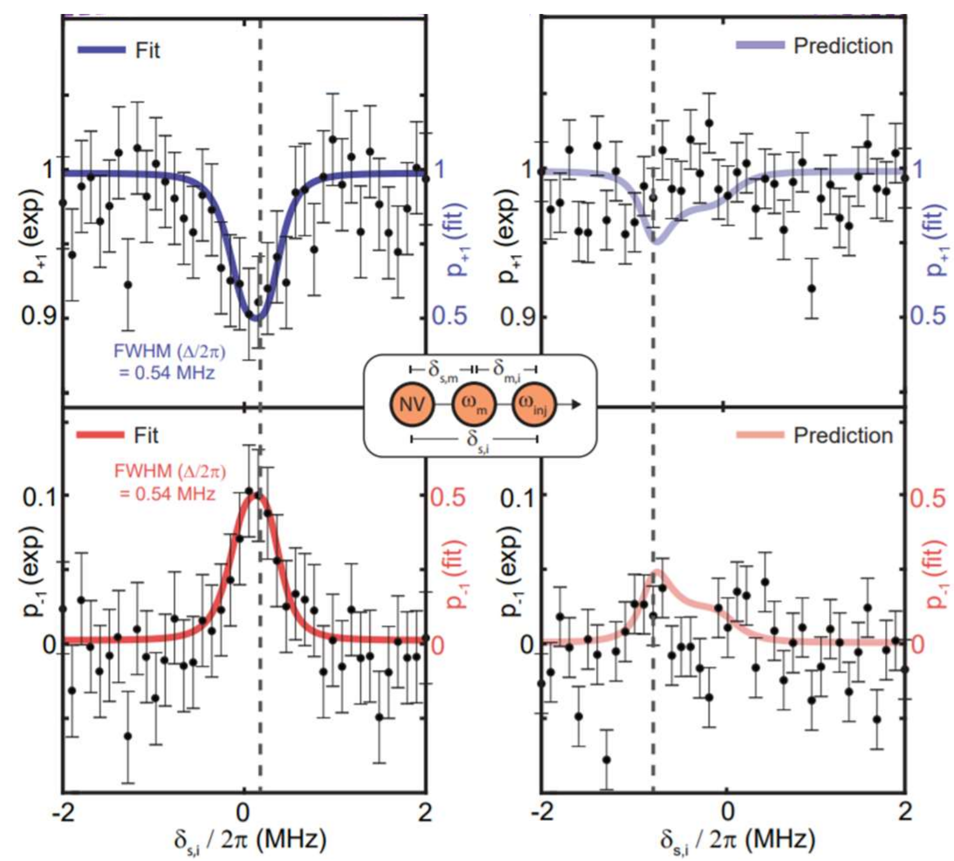


Shandilya, Lake et al. Nature Physics 2021

Demonstration of optomechanical spin driving

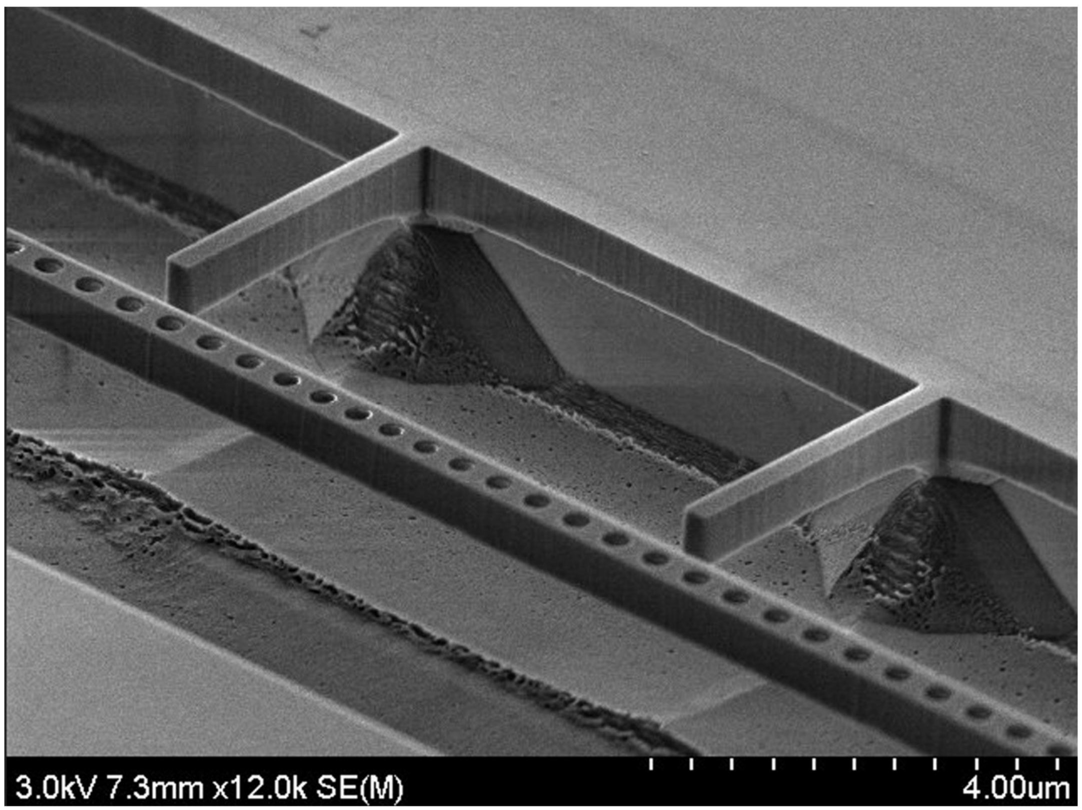


Shandilya, Lake et al. Nature Physics 2021



Future direction: enhancing efficiency by 10^{10}

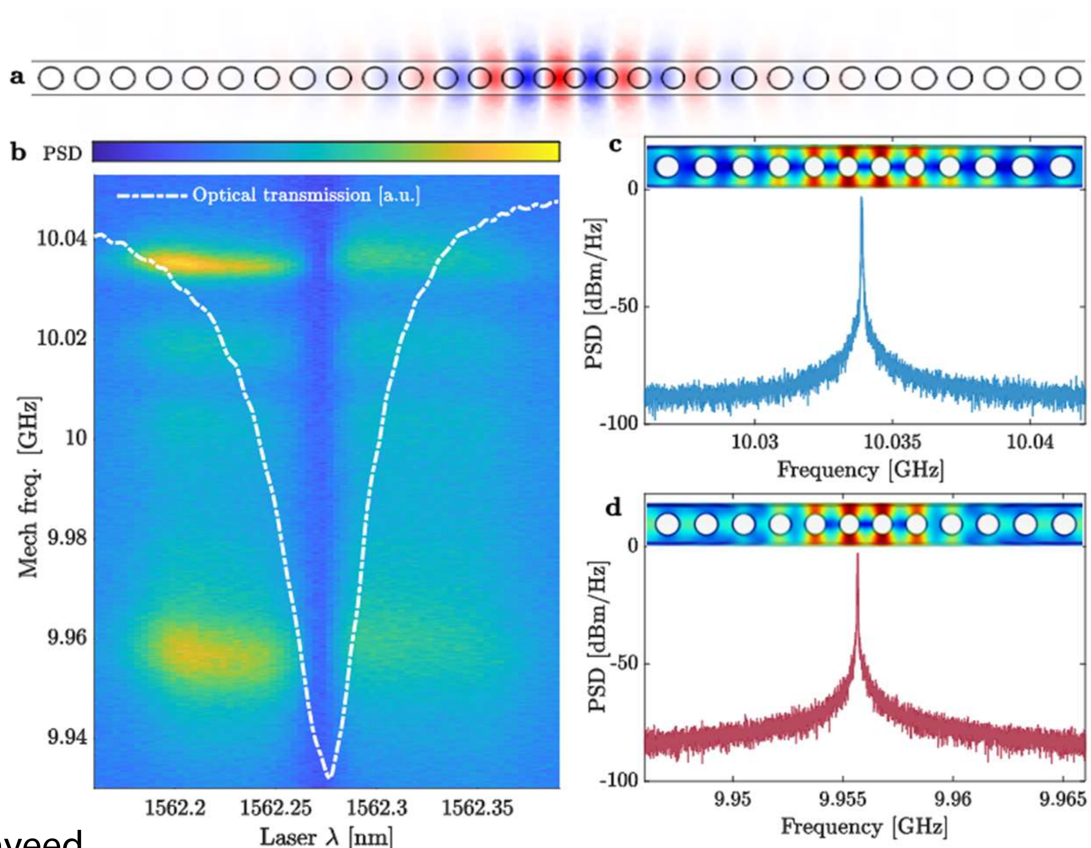
Optomechanical crystals: boost cooperativity by orders of magnitude



Elham Zohari, Joe Losby

Future direction: enhancing efficiency by 10^{10}

Optomechanical crystals: boost cooperativity by orders of magnitude



Elham Zohari, Waleed El Sayeed

Diamond photonics: new opportunities

Routinely drop > 100 mW power into cavities with Q ~ 10^5

Opens doors to nonlinear phenomena…

Second (!) and third harmonic generation

Many phonon processes

…and to quantum sensing

Torque magnetometry

NV magnetometry with IR light

Team

Postdoctoral scholars

Joe Losby
Natália Do Carmo Carvalho
Sigurd Flagan
Vinaya Kavatamane

Graduate Students

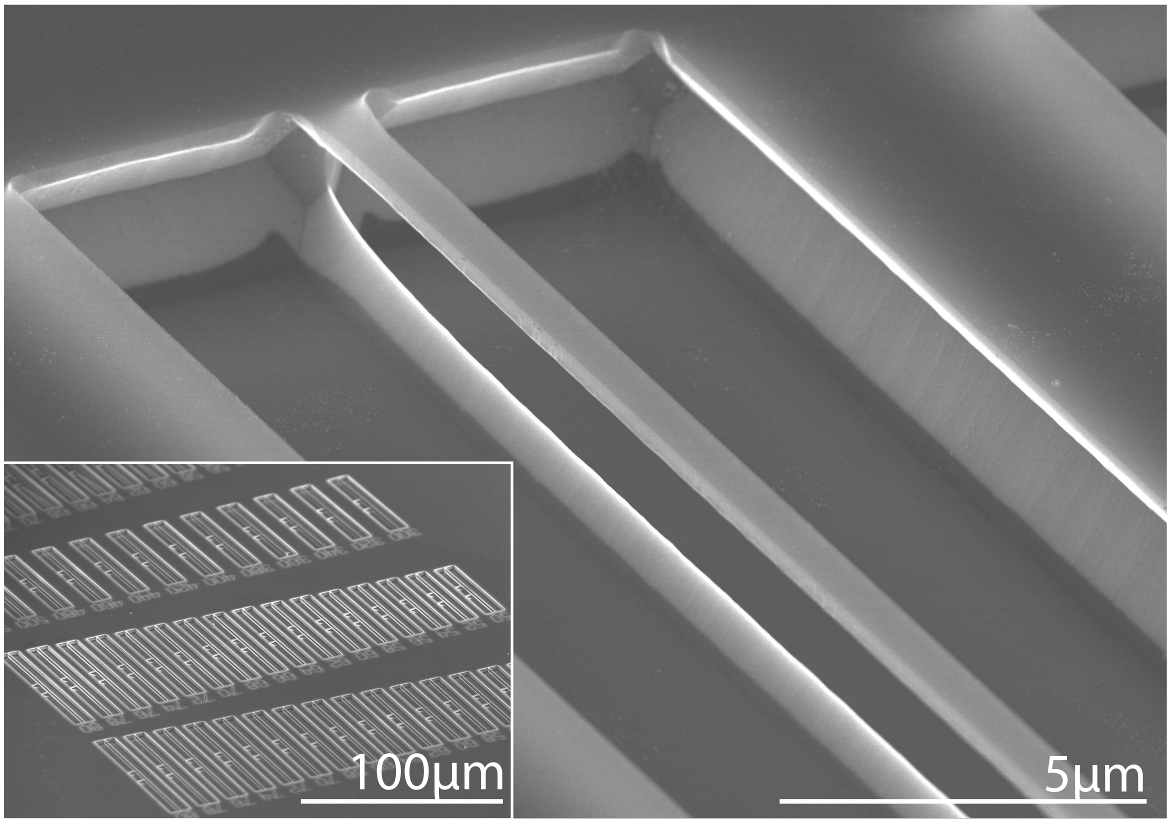
Elham Zohari (at UofA)
Bishnu Behera
Prasoon Shandiliya
Xinyuan Ma
Parisa Behjat
Peyman Parsa
Waleed El Sayeed
Joe Itoh
Ahmas El-Hamamsy

Spin-mechanics alumni

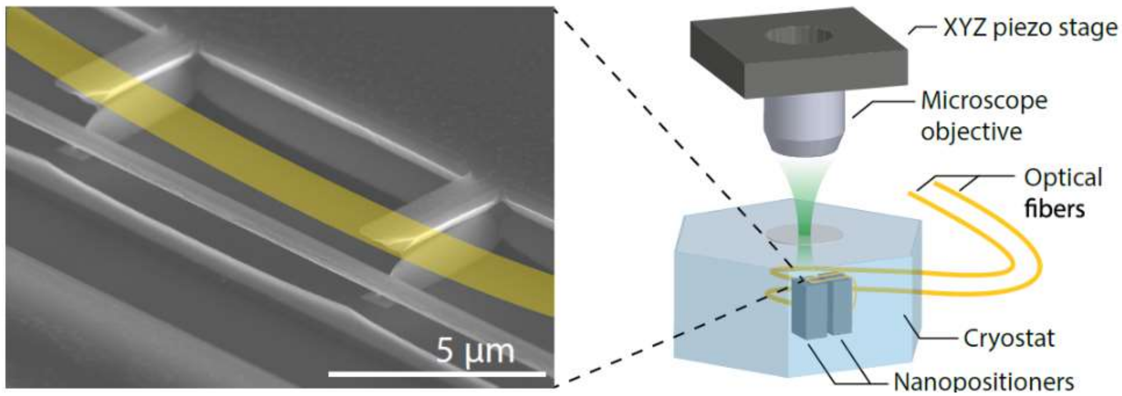
Denis Sukachev (now at AWS Quantum)
David Lake (now at Caltech)
Matthew Mitchell (now at UBC)

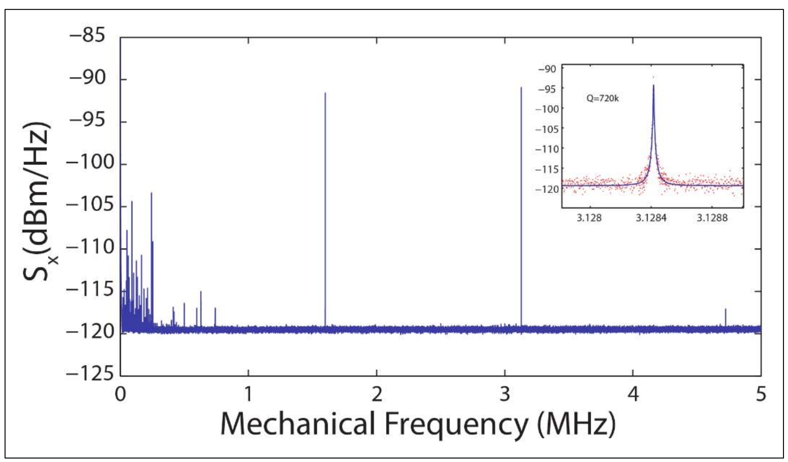
PDFs + PhDs: join us!

Single crystal diamond nanobeams



Diamond waveguide optomechanics

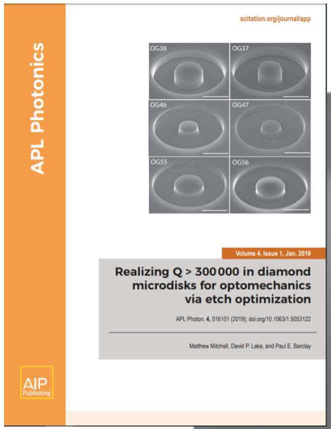


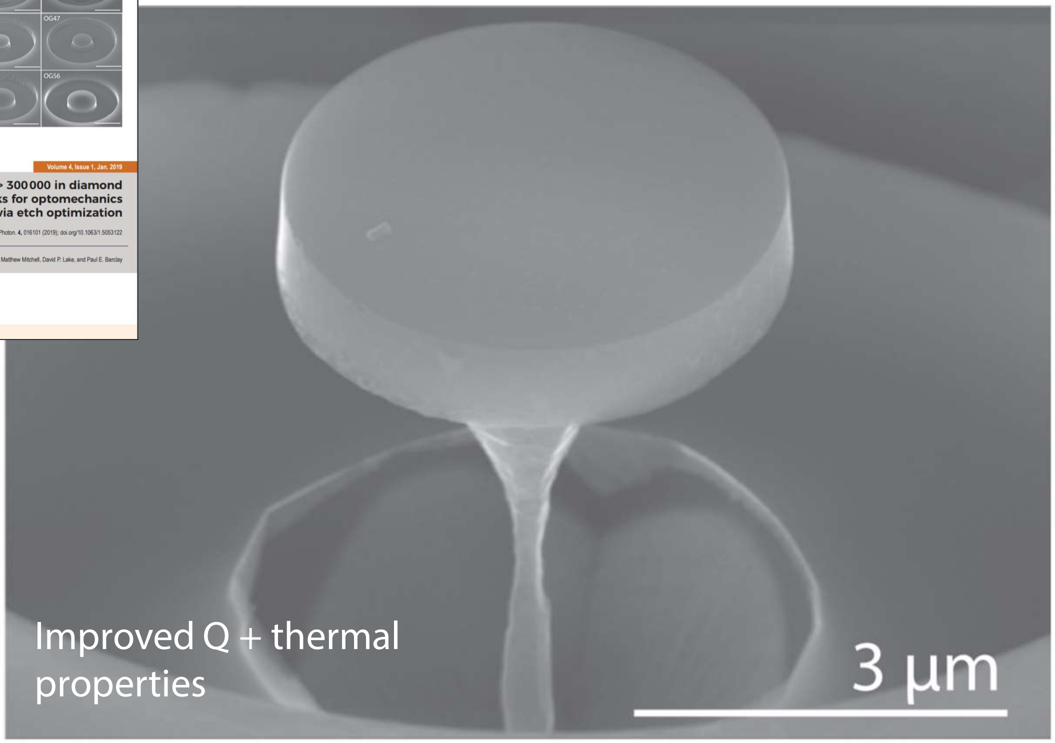


Q > 700,000

Readout sensitivity ~ fm/Hz$^{0.5}$

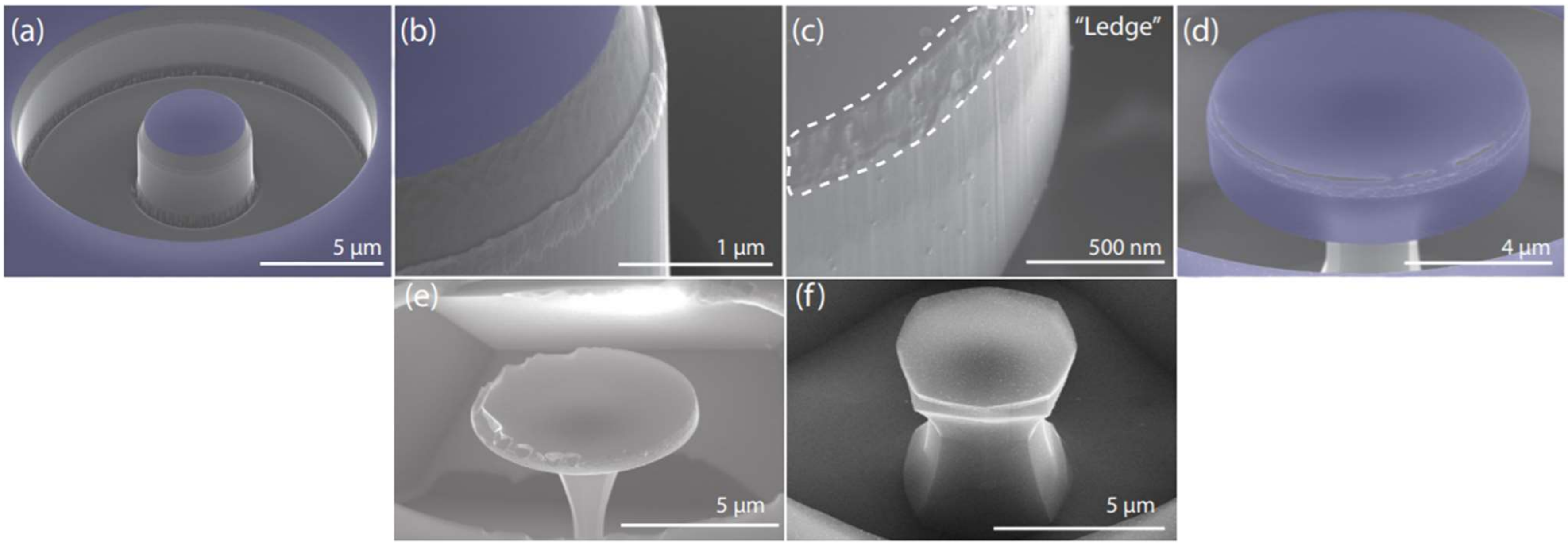
Reaching C ~ 3 with optimized devices



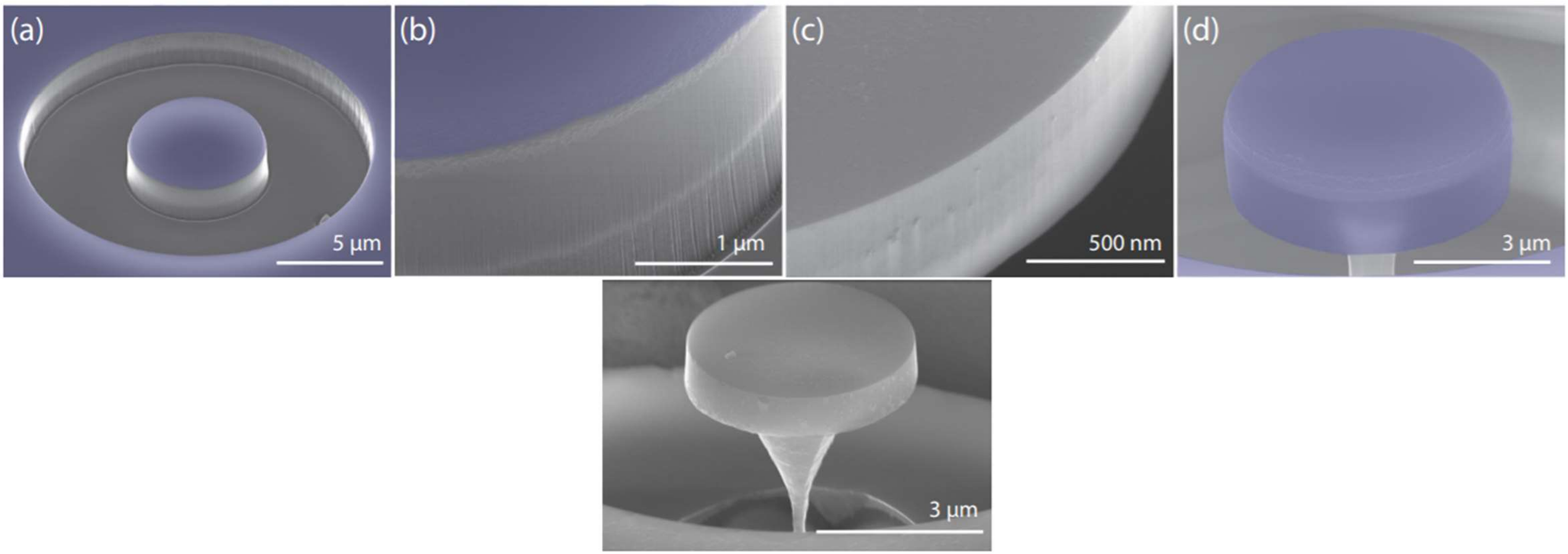


M. Mitchell, D. Lake, P.E. Barclay, APL Photonics 4, 016101 (2019)

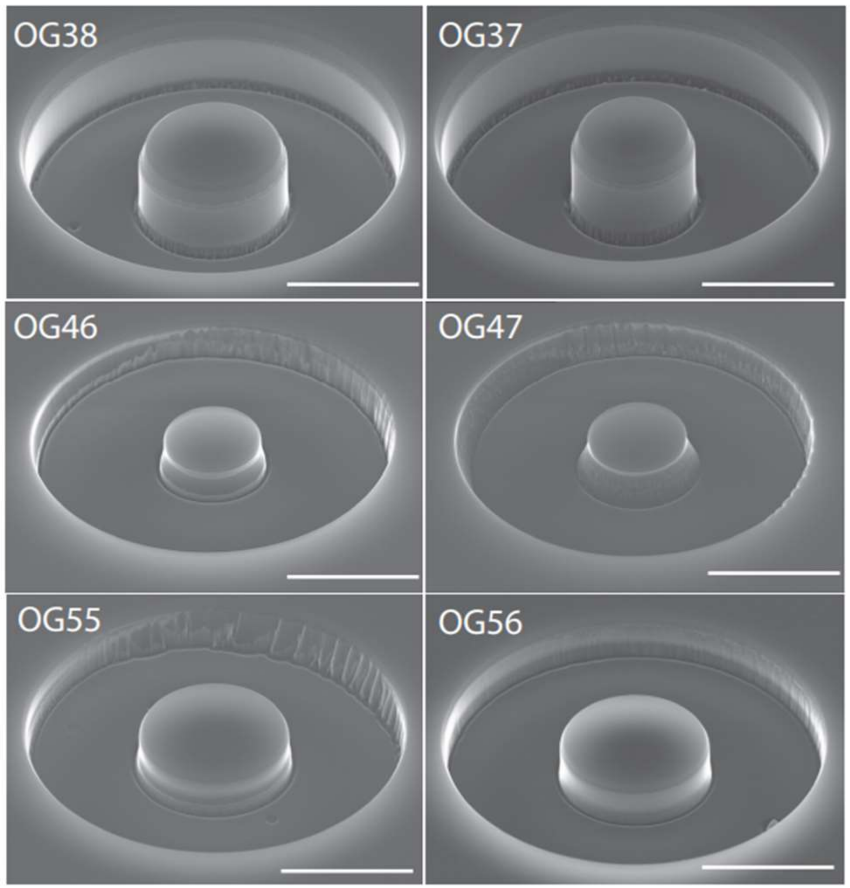
Hard mask optimization



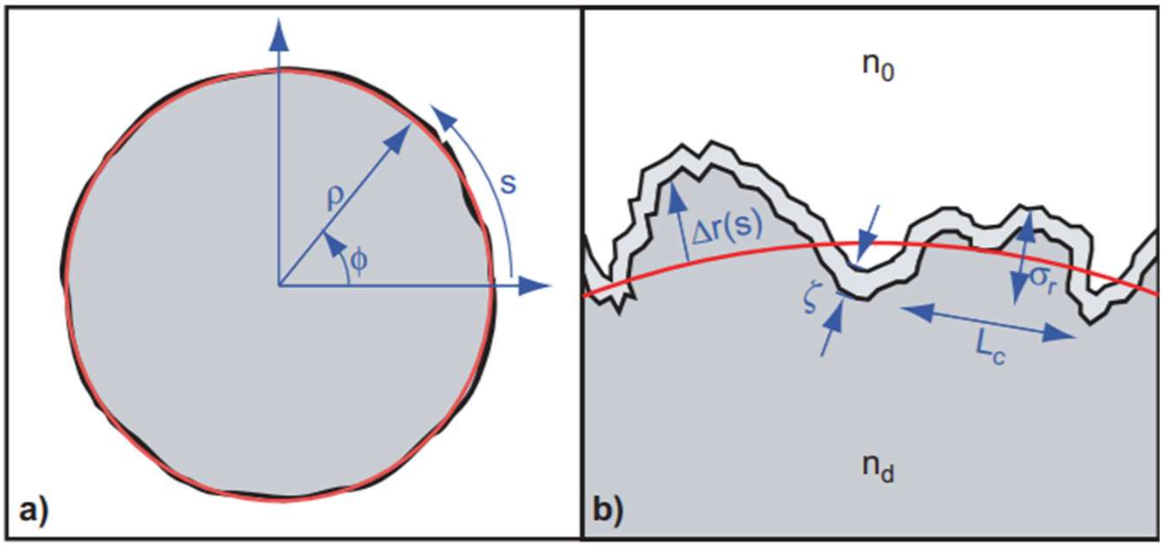
Hard mask optimization



Diamond etch optimization



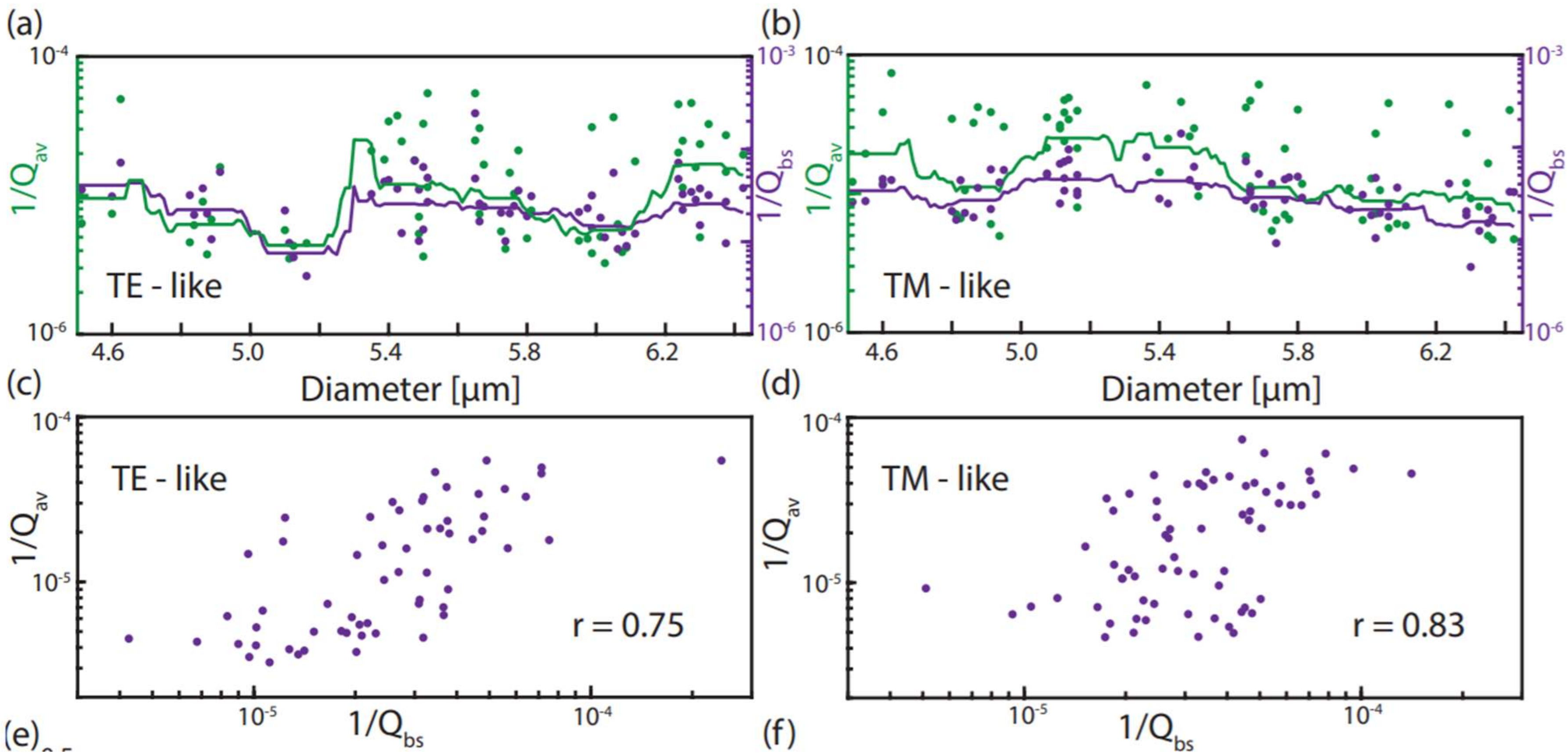
Probing surface roughness



Beyond the Rayleigh scattering limit in high-*Q* silicon microdisks: theory and experiment

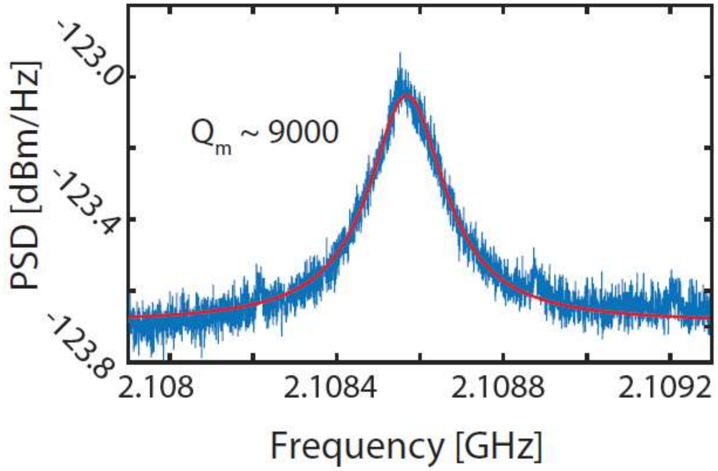
Matthew Borselli, Thomas J. Johnson, and Oskar Painter
Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA.
borselli@caltech.edu

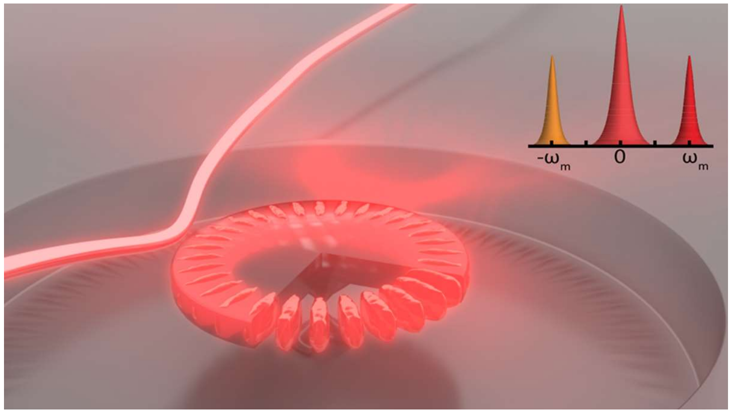
Probing surface roughness

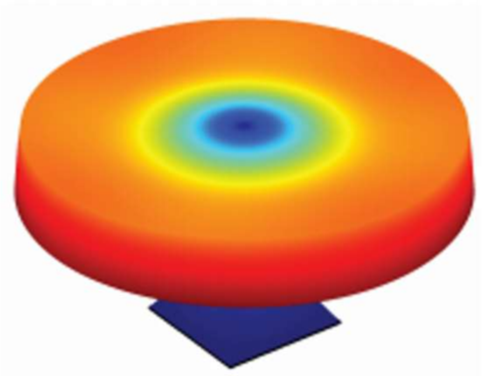


Diamond microdisk cavities: optomechanics

Transduced thermal (kT) motion:







Phonons
2.1 GHz

Measure GHz vibrations with fm/Hz$^{1/2}$ sensitivity

Room-T Q*f > 10^{13} (ambient conditions)

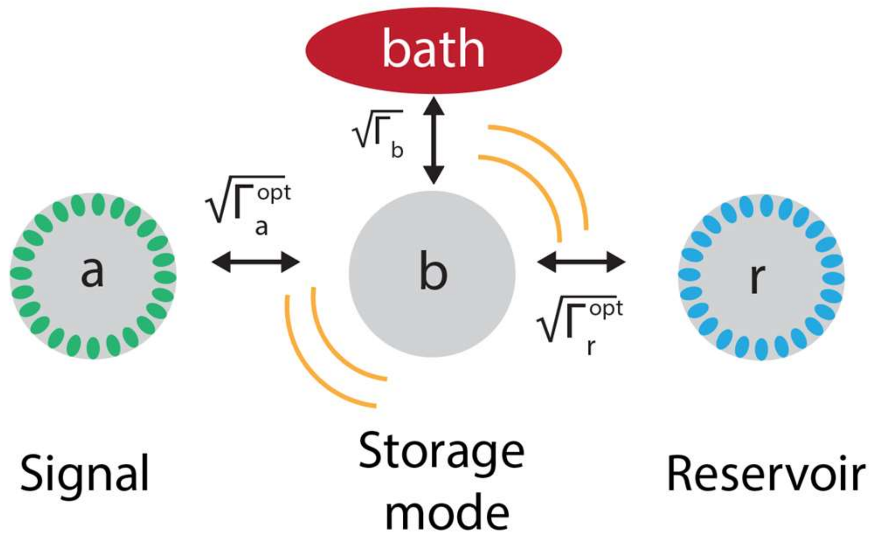
Operating in resolved sideband regime

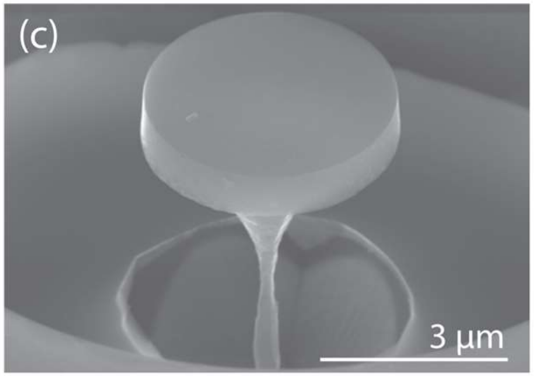
Microsecond (μs) phonon lifetime

Mitchell et al. Optica (2016)

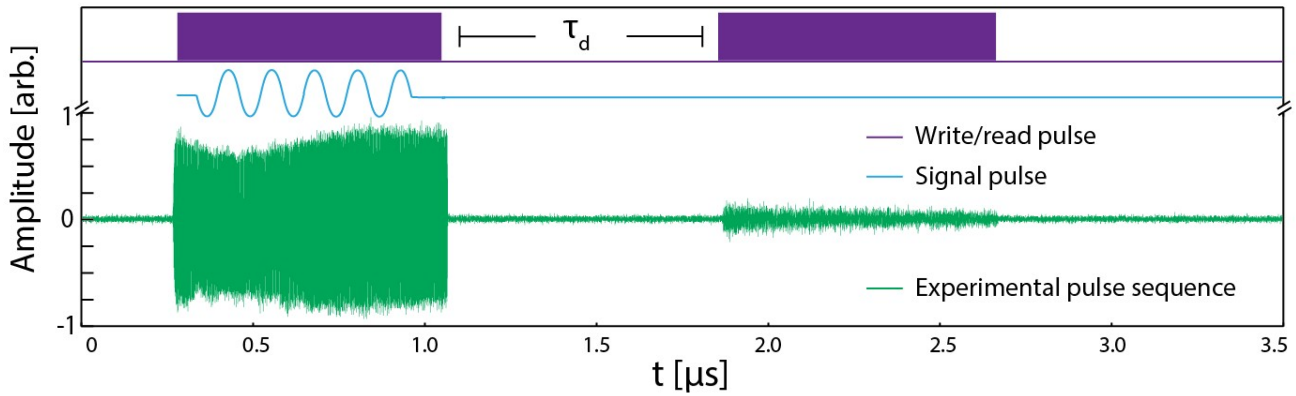
Optomechanics for information processing

Storing + manipulating light





Optomechanical pulse storage



Transfer signal from optical to mechanical domain

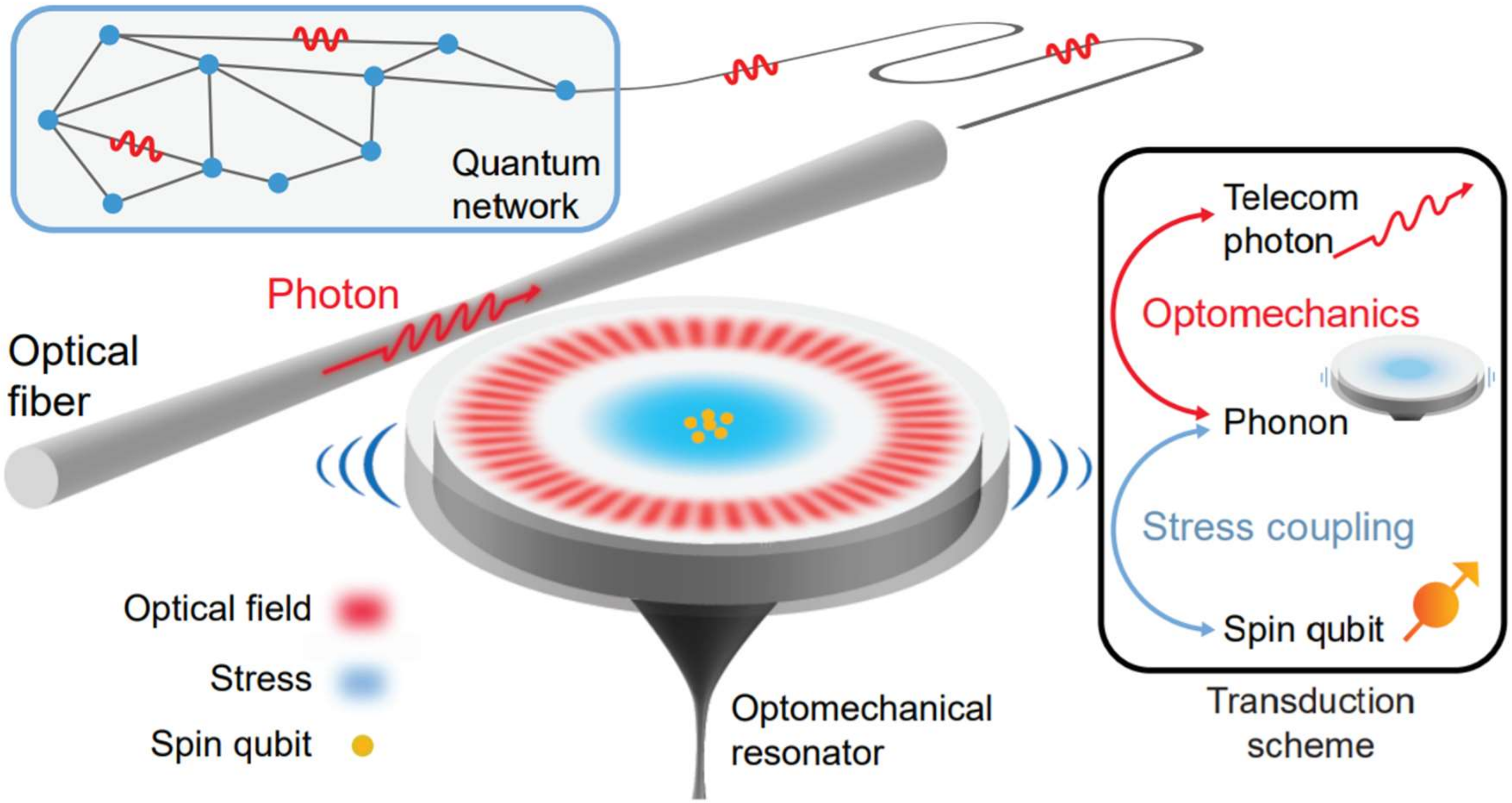
Store in mechanical oscillation

Readout optically

Lake, Mitchell, Sukachev, Barclay, Nature Communications (2021)

Also see: work from Hailin Wang (Oregon), Sussman (NRC Ottawa)

Optomechanical spin control

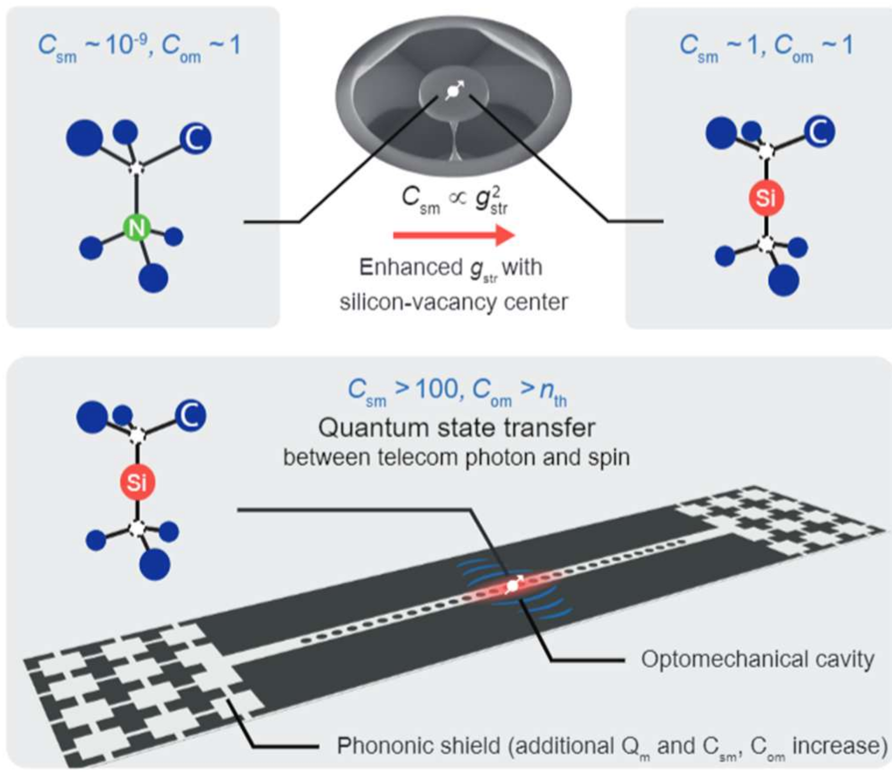


Shandilya, Lake et al. arXiv:2102.04597

Future directions

Currently: spin-phonon coupling is weak (~ 1 Hz)

Shift to SiV or other spins to realize a quantum interface (see Loncar)



Team

PDFs

Ghazal Haji salem
Wei Zhang
Joe Losby
Denis Sukachev (now at MIT/Harvard)

Graduate Students

Elham Zohari
Hamidreza Kaviani
David Lake (now at Caltech)
Matthew Mitchell (now at UBC)
Bishnu Behera
Prasoon Shandiliya
Blaine McLaughlin
Anustup Das
Xinyuan Ma

Alumni

Gustavo de Oliveira Luiz (moving to NanoFAB)
Aaron Hryciw (now at NanoFAB)
Behzad Khanaliloo (now at Lumerical)
JP Hadden (now at Sussex)
Harishankar Jayakumar (now at CCNY)

Etch conditions: anisotropic etch

Sample	ICP [W]	RF [W]	Bias [V]	Etch Rate [nm/s]	Sidewall Angle [°]	Parameter Sweep
OG47	850	20	130	1.534	15.55	RF–α
OG46	850	40	190	1.636	6.509	
OG38	850	60	230	1.911	2.976	
OG36	850	80	279	1.620	1.107	
OG37	850	100	311	1.759	0.636	
OG54	850	80	281	2.206	13.27	ICP
OG53	1000	90	286	2.454	4.063	
OG48	1150	100	291	3.225	6.952	
OG49	1300	110	293	4.062	8.994	
OG55	1000	100	304	2.685	3.242	RF–β
OG56	1000	110	319	2.378	2.634	